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Reducing Long-Term Costs While Preserving a Robust Strategic Airlift Fleet

Options for the Current Fleet and Next-Generation Aircraft

Christopher A. Mouton, David T. Orletsky,
Michael Kennedy, Fred Timson

Prepared for the United States Air Force
Approved for public release; distribution unlimited

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Preface

This document reports the findings of a fiscal year 2010–2011 RAND Project AIR FORCE study, "U.S. Air Force (USAF) Intertheater Airlift Fleet Recapitalization Strategy."[1] In this study, we conducted a cost-effectiveness analysis to determine the best way to recapitalize the USAF intertheater (strategic) airlift fleet.

The USAF intertheater airlift fleet comprises C-5s and C-17As. This fleet has been used more heavily since the attacks on September 11, 2001, as a result of overseas contingency operations. As a result, some aircraft will reach their flight hour limits earlier than initially expected, and recapitalization of the fleet will be required to maintain capability. One option is the development and procurement of a new military airlifter, notionally called "C-X." This would require a large capital outlay for research and development and early production units. Given the current downward pressure on the defense budget and the need to recapitalize other portions of the USAF fleet, adequate funding may not be available. Further, annual funding profiles may need to be "flattened" or "deconflicted" with other USAF programs to fit in the overall USAF budget. This study examined a broad range of potential aircraft alternatives and considered a number of permutations on USAF plans for the current fleet, including a reduced requirement and retirement of all C-5As, to determine how best to recapitalize this

1 A companion volume to this document contains two additional appendixes. See Christopher A. Mouton, David T. Orletsky, Michael Kennedy, and Fred Timson, *Reducing Long-Term Costs While Preserving a Robust Strategic Airlift Fleet: Appendixes C and D*, Santa Monica, Calif.: RAND Corporation, MG-1238/1-AF, forthcoming, Not available to the general public.

fleet. This study analyzed both the net present value life-cycle cost and annual funding profiles of the options considered. Conclusions and recommendations are based on both of these measures.

The research described in this document was sponsored by Gen Raymond E. Johns, Jr., Commander, Air Mobility Command, Scott Air Force Base, Illinois. The study was performed within the Force Modernization and Employment Program of RAND Project AIR FORCE.

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Summary

This document presents the results of a cost-effectiveness analysis to determine the best way to recapitalize the USAF intertheater (strategic) airlift fleet. The USAF intertheater airlift fleet consists of C-5s and C-17As. As of 2010, there were 111 C-5s in the inventory; as of 2012, there will be 221 C-17As.[1] Three versions of the C-5 were produced: the C-5A; C-5B; and two special-mission aircraft, C-5Cs.[2] The C-5 fleet is currently undergoing a modernization program to upgrade its avionics, engines, and other components. After an aircraft undergoes this Reliability Enhancement and Reengine Program (RERP), it is designated a C-5M. One C-5A and seven C-5Bs have undergone this upgrade and are now so designated. As of fall 2010, the USAF had 59 C-5As,[3] 42 C-5Bs, two C-5Cs, and eight C-5Ms. The current USAF plan for the

[1] U.S. Department of Defense and U.S. Transportation Command, "Mobility Capabilities and Requirements Study: Executive Summary," 2010. There has been one C-17A hull loss, and one C-17A operates as part of the NATO Strategic Airlift Capability (SAC) bringing the total aircraft in inventory down from 223 to 221. (Pacific Air Forces, "Excutive Summary: Aircraft Accident Investigation, C-17A, T/N 00-0173," Joint Base Elmendorf-Richardson, Alaska, July 28, 2010; the Ministry of Defence of the Republic of Bulgaria, et al., *Memorandum of Understanding Concerning Strategic Airlift Capabillity*, September 2008.)

[2] The C-5Cs were built early in the production run of the C-5As. For our purposes, we considered them equivalent to C-5As and therefore simply count them as C-5As before they are RERPed and as C-5Ms after they are RERPed.

[3] The National Defense Authorization Act for Fiscal Year 2012 authorized retirement of additional aircraft to reduce the C-5A fleet to 27 (Public Law 112-81, National Defense Authorization Act for Fiscal Year 2012, December 31, 2011), and the Air Force is seeking to retire all C-5As ("Air Force Requests C-5 Retirement Authority, Predicts $1 Billion in Savings," *Inside Defense*, March 16, 2012). In light of these developments and the ongoing debate, we conducted a sensitivity analysis to look at this very issue. We found that the results

C-5 fleet is to implement the RERP upgrade on all the C-5Bs and to retire 22 of the C-5As. Note that a RERP does not affect the service life of the aircraft. The resulting fleet will consist of 37 C-5As and 52 C-5Ms (one of which is an upgraded C-5A, two of which are upgraded C-5Cs, and the rest are upgraded C-5Bs). This fleet is sufficient to meet the demands of Mobility Capabilities and Requirements Study 2016 (MCRS-16) Case 1.

This reasearch was undertaken because of concerns that much of the current fleet is reaching the end of its service life in the next few decades and concerns about a budgetary spike that would result from the need to recapitalize. For nearly a decade, as a result of overseas contingency operations, the C-17As have flown significantly more hours than they did before September 11, 2001. The availability of the C-5s—especially the C-5As—has been an ongoing and significant problem affecting the capability of the airlift fleet. In future years, the aging of the current fleet will mean that some recapitalization actions will have to be taken.

We examined a broad range of potential aircraft alternatives and considered a number of permutations of USAF plans for the current fleet, including a reduced requirement and retirement of all C-5As, to determine how best to recapitalize this fleet. The analysis included both the net present value life-cycle cost (NPVLCC) and annual funding profiles of the options considered. Conclusions and recommendations are based on both of these measures.

Current Fleet Retirement Schedule

We projected the retirement schedule for the current fleet to determine when new aircraft would need to be added to retain the required capability.[4] The baseline retirement schedule was determined using each

presented in the document are not sensitive to C-5A retirements, and the overall conclusions are independent of these retirements.

[4] Two Air Force Materiel Command organizations supplied equivalent flight hours (EFH) data to us: Aeronautical Systems Center's C-17 Engineering Branch provided EFH for each

aircraft's current accumulated flight hours, their average severity, and a projection of future hours and severity for every aircraft to determine when that aircraft will reach a life-limiting constraint due to structural fatigue. For the C-5, different aircraft have different life-limiting components. Eight components are tracked to determine which component will be the life-limiter and when each C-5 will need to be grounded (or flight restrictions need to be imposed) based on the current flight limits.[5] In contrast, all C-17As have the same two potential structural problems: the aft fuselage and the upper wing skin. The problem with the aft fuselage of the C-17A is only a modest concern and will likely require a minimal fix that involves cold working of the rivet holes and other fairly well-understood procedures. As a result, the upper wing skin is considered the life-limiting component of the C-17A.

We projected the remaining years of life for each airframe to determine the number of retirements that could be expected each year through the life of the current fleet. Figure S.1 shows our projections through 2060. The figure shows that the C-17As are the first aircraft to reach end of life, starting in the mid-2030s. The C-5Ms then begin to reach their life limit and will be retired beginning at the end of the drawdown of the C-17A fleet. Since the C-5As are being flown just over 300 hours per year, these aircraft will not reach their structural life-limit for many years.[6]

We used this fleet drawdown as the baseline for our analysis. Permutations of this schedule, including different C-5A retirement dates, C-17A production rates, and RERP plans for C-5A and C-5B, were used to explore different cases to understand how the answer might

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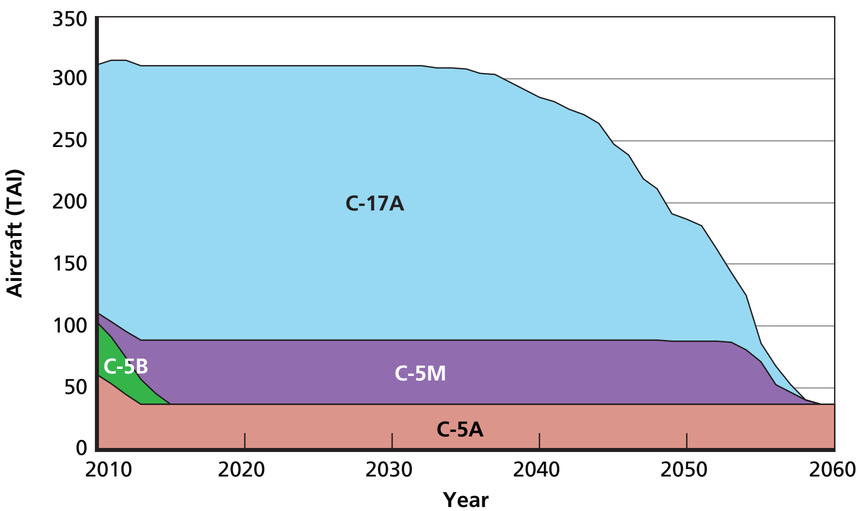
tail and other relevant information on the C-17A fleet (EFH data current as of June 30, 2010); and Warner Robins Air Logistics Center provided EFH data for each tail and other relevant information on the C-5 fleet (EFH data current as of October 26, 2010).

[5] The eight components tracked for the C-5 include total pressure cycles, the upper aft crown, the inner wing upper, the inner wing lower, the outer wing upper, the outer wing lower, the horizontal tail, and the vertical tail.

[6] This chart shows only life limits that are due to structural fatigue. It is likely that the C-5A will be retired for a reason other than structural fatigue at some point before the aircraft reach their structural limit, unless upgrades are done and, as a result, the C-5A begins to fly significantly more hours.

Figure S.1
Projected Retirement Profile of Current Fleet



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change under different circumstances and to understand the robustness of the answers.

Aircraft Alternatives and Fleet Options

We examined a broad range of potential aircraft alternatives. These represent a broad spectrum of aircraft types, including current-inventory aircraft, commercial-derivative aircraft, foreign military aircraft, and future-design aircraft incorporating a range of technology options and other fleet derivative aircraft. We considered 15 aircraft alternatives, shown in Table S.1. In addition to the aircraft shown in the table, we also considered a service-life extension program (SLEP) for the C-17A.

These 15 aircraft included three current-inventory aircraft: the C-5A/B, C-5M, and C-17A. For the purposes of the effectiveness analysis, we assumed that the C-5A and C-5B have the same flight characteristics (but different availabilities). A C-17A derivative aircraft known as the C-17FE was also analyzed. The C-17FE is essentially

Table S.1
Aircraft Alternatives Considered

Current Inventory[a]	Commercial Derivative	Foreign Military	Future Design	Current Technology New Design[b]	Other
C-5A/B (Lockheed Martin)	C-767 (Boeing 767-300F)	A400M (EADS)	BWB-100++ (Boeing very advanced large blended-wing body)	C-84X (Identical to C-5M, but new design for costing)	C-17FE (Boeing C-17A narrow-body derivative)
C-5M (Lockheed Martin)	C-777 (Boeing 777F)	An-124 (Antonov)	BWB-100 (Boeing very advanced medium blended-wing body)	C-59X (Identical to C-17A, but new design for costing)	
C-17A (Boeing)	C-747 (Boeing 747-8F)	IL-76MF (Ilyushin)	SBW-75 (Lockheed Martin medium technology box wing)		

[a] C-5C aircraft are analyzed and counted as C-5A aircraft in this study.

[b] The C-59X and the C-84X have the same performance, weight, and characteristics of the C-17A and C-5M, respectively. These aircraft were considered new designs for costing meaning that a full R&D program would need to be executed without reliance on heritage designs.

a narrow-body C-17A with increased fuel efficiency and better short- and soft-field capabilities. The analysis considered three commercial-derivative freighter aircraft: the 767-300F, the Boeing 777, and the Boeing 747-8F. These aircraft are designated the C-767, C-777, and C-747, respectively, to highlight the fact that they are militarized aircraft based on their respective commercial counterparts. We also analyzed three foreign military aircraft: the European Aeronautic Defence and Space Company's A400M, the Antonov An-124-100M-150, and the Ilyushin Il-76MF. The An-124-100M-150 (denoted simply as An-124 in the table) is a commercial version of the An-124 fitted with Western avionics and is most similar to the C-5. The Il-76MF is a stretched variant of the Il-76 and most closely resembles the Boeing C-17A. We considered three new future-design aircraft: two blended-wing body (BWB) options from Boeing (the BWB-100 and the BWB-100++) and the Lockheed SBW-75 box-wing aircraft. These aircraft represent varying levels of technology—the BWBs represent a significant technological leap, while the SBW-75 represents a more modest technological advancement.

We also considered current-technology aircraft with the C-59X and the C-84X that have the same performance, weight, and characteristics as the C-17A and C-5M, respectively.[7] For the purposes of costing, the C-59X and C-84X were considered new designs, meaning that a full research and development program would need to be executed that would not rely on heritage designs. As a result, the learning curve would start at the beginning.

These aircraft alternatives represent a wide range of sizes, with maximum gross takeoff weights ranging from just over 300,000 lbs to nearly 1,000,000 lbs. Some of these aircraft alternatives cannot carry all the cargo that the current fleet of C-5s and C-17As can carry, specifically, what is commonly referred to as oversized and outsized cargo.[8]

[7] These options were developed for this study and the designation is simply based on maximum gross weight.

[8] In this document, the term *oversized and outsized* is defined relative to a particular alternative. Specifically, for each alternative that is not capable of carrying all the cargo, all the cargo that cannot fit on that alternative is considered to be oversized and outsized. This study does

Examples of this type of cargo include helicopters; cranes; howitzers; 40-foot containers; low-bed semitrailers; and construction equipment, such as tractor scrapers, excavators, and graders.[9] Therefore, we considered both single-aircraft fleets and mixed-fleet options. The aircraft alternatives that cannot carry all the cargo must be paired with other aircraft to carry out the full requirement and therefore must be part of a mixed fleet. Other aircraft are capable of transporting all the cargo. These aircraft could be part of a mixed aircraft fleet or single-aircraft fleet. We examined these alternative fleets through a range of potential fleet retirement schedules and changes to the current plan, including extending C-17A production beyond 2012 and changes in the C-5 RERP program.

Methodology

The methodology we used was broadly similar to that for past recapitalization studies RAND Project AIR FORCE conducted for USAF.[10] This methodology had four major analytical pieces:

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not impose an artificial definition of this term, and each alternative is allowed to carry all the cargo that can fit in it.

9 MCRS-16 examined the entire mobility problem and therefore moved much of the larger and heavier equipment by sea. The current study examines only the items that MCRS-16 identified as needing to move by air.

10 We first evaluated options to recapitalize the USAF aerial refueling aircraft in the KC-135 Recapitalization Analysis of Alternatives, completed in early 2006. The results of that study were that the total cost of maintaining aerial refueling capability is insensitive to the timing of recapitalization and that, therefore, decisions about that timing should be made on other grounds, such as technical risk, some extra capabilities associated with new tankers, and the tightness of the overall U.S. Department of Defense budget in different times. See Michael Kennedy, Laura H. Baldwin, Michael Boito, Katherine M. Calef, James S. Chow, Joan Cornuet, Mel Eisman, Chris Fitzmartin, Jean R. Gebman, Elham Ghashghai, Jeff Hagen, Thomas Hamilton, Gregory G. Hildebrandt, Yool Kim, Robert S. Leonard, Rosalind Lewis, Elvira N. Loredo, Daniel M. Norton, David T. Orletsky, Harold Scott Perdue, Raymond A. Pyles, Timothy L. Ramey, Charles Robert Roll, Jr., William Stanley, John Stillion, Fred Timson, and John Tonkinson, *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Summary Report*, Santa Monica, Calif.: RAND Corporation, MG-455-AF, December 2005, Not available to the general public; and Michael Kennedy, Laura H. Baldwin, Michael Boito,

- Determine the retirement profile of the current fleet.
- For each aircraft alternative or set of alternatives, determine the number of aircraft required to meet the strategic airlift requirement.
- Determine the yearly procurement for each alternative needed to meet the overall requirement, based on the retirement profile.
- Cost each fleet for each retirement profile.

The baseline retirement profile we used was discussed earlier. Other retirement profiles were considered as excursions.

The number of each aircraft alternative was calculated to meet the airlift requirement from the most recent requirement for organic strategic airlift, as defined in MCRS-16 Case 1.[11] In the MCRS-16 Case 1 scenarios, U.S. forces conduct two nearly simultaneous large-scale land campaigns and respond to three nearly simultaneous homeland defense consequence-management events with corresponding aerospace control levels and maritime awareness presence levels, which are concurrent with the land campaigns.

We modeled the actual cargo in this case and determined the cargo that could be carried based on the internal dimensions of each aircraft alternative. Cargo weight was used to calculate the average weight carried on each route to determine aircraft fuel burn, flight

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Katherine M. Calef, James S. Chow, Joan Cornuet, Mel Eisman, Chris Fitzmartin, Jean R. Gebman, Elham Ghashghai, Jeff Hagen, Thomas Hamilton, Gregory G. Hildebrandt, Yool Kim, Robert S. Leonard, Rosalind Lewis, Elvira N. Loredo, Daniel M. Norton, David T. Orletsky, Harold Scott Perdue, Raymond A. Pyles, Timothy L. Ramey, Charles Robert Roll, Jr., William Stanley, John Stillion, Fred Timson, and John Tonkinson, *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Executive Summary*, Santa Monica, Calif.: RAND Corporation, MG-495-AF, 2006.

The second analysis was conducted as part of the USAF Intratheater Airlift Fleet Mix Analysis, completed in late 2007. The results of that study were that conducting a SLEP on the combat-delivery C-130E and C-130H1 models is less cost-effective than replacing them with new C-130J-30s with equivalent capability. See Michael Kennedy, David T. Orletsky, Anthony D. Rosello, Sean Bednarz, Katherine Comanor, Paul Dreyer, Chris Fitzmartin, Ken Munson, William Stanley, and Fred Timson, *USAF Intratheater Airlift Fleet Mix Analysis*, Santa Monica, Calif.: RAND Corporation, MG-824-AF, October 2010, Not available to the general public.

[11] U.S. Department of Defense and U.S. Transportation Command, 2010.

time, and any required refueling stops. For some aircraft alternatives, we note the amount of cargo that could not be carried because of size limitations. We computed the peak aircraft requirement for all alternatives and then computed an equivalency ratio relative to the C-5M for each aircraft alternative (for the cargo the alternative can carry) to make comparisons among aircraft straightforward. The final result for each aircraft alternative of this part of the analysis is (1) a "C-5M equivalency" and (2) a "C-5M residual." The C-5M residual is the number of C-5Ms required to carry the cargo that the alternative could not carry for size reasons.

Using our retirement profile for the current fleet and the C-5M equivalency and the C-5M residual, we could then compute the procurement profile (number of aircraft procured per year) for each alternative for the fleet to meet the Case 1 requirement for all years in this analysis. In the case of an alternative that cannot carry all cargo (i.e., has some C-5M residual), the aircraft in the current fleet will be able to carry the residual cargo for some time. However, as more retirements occur, a point will come when another large aircraft will need to be procured to carry this cargo. We then determined the total NPVLCC of each alternative fleet. The fleet that meets the requirement at the lowest cost is the most cost-effective alternative fleet. In addition, we performed a sensitivity analysis to ensure that the most cost-effective fleet is also a robust solution.

In addition to NPVLCC, we computed funding profiles for each year in the analysis. In many instances, large spikes in yearly spending may not be acceptable. We considered cases to smooth the funding profile and then determined how this affected NPVLCC.

Results

This analysis led to a series of conclusions. A highly advanced conceptual-design aircraft (specifically, a high-proportion composite BWB) is the most cost-effective option for all current fleet retirement profiles analyzed and for all sensitivities we varied. Under baseline assumptions, this option results in a cost savings of nearly $40 billion

(FY 2011) NPVLCC over a new-design C-5M aircraft. But this is a highly advanced aircraft, and its development presents a significant technological risk. Appendix C in the companion volume details this technological risk in terms of empty weight fraction, weight specific range, and percent composites.[12]

Absent a new, revolutionary aircraft design, we found that procurement of a commercial-derivative aircraft for bulk cargo followed by later procurement of an outsize and oversize cargo-capable aircraft is the most cost-effective option. This conclusion held even for the C-84X, the current-technology aircraft with the same performance as the C-5M but incorporating the cost of a full research and development program. Further, the commercial-derivative aircraft followed by the highly advanced aircraft (the BWB) is only slightly less cost-effective than procurement of a single-aircraft fleet consisting of the BWB alone. This strategy, therefore, provides a hedge against the technical risk of the advanced aircraft. The strategy also has the advantage of delaying the peak in annual procurement spending. The procurement bow wave, defined as a significant increase in annual expenditures due to research, development, test, and evaluation spending and initial procurement, can be delayed by 10 to 15 years in this case.

Continuing production of the C-17A at a low rate could delay and flatten the procurement bow wave. The idea here was to keep the production line open while getting a few aircraft per year and having the ability to increase production when required. We looked at two options: procuring two C-17As per year and procuring six C-17As per year. This option is inferior according to all measures of effectiveness we considered: Low-rate C-17A production has higher NPVLCC, earlier peak spending, and higher near-term cost.

We also considered the possibility of SLEPing the C-17A past the current service life. Since there are currently no SLEP options for this aircraft, we did the cost-effectiveness analysis parametrically, based on a 45,000 to 60,000 EFH SLEP, by determining the cost at which a SLEP would be cost-effective relative to the base case, procuring a new aircraft. SLEPing the C-17A is cost-effective if the SLEP cost is

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12 Mouton et al., forthcoming.

between $35 million to 95 million, depending on the follow-on aircraft option that is available and chosen.

RERPing the C-5s is beneficial regardless of recapitalization strategy. Specifically, we found that RERPing the C-5Bs into C-5Ms is cost-effective. We also found that that RERPing a portion of the C-5A fleet would be cost-effective if the cost and resulting availability were similar to those for RERPing the C-5Bs.

To summarize these key findings:

- A highly advanced and mostly composite BWB was the most cost-effective future aircraft, although the most technologically risky.
- Absent a revolutionary new aircraft, a commercial-derivative aircraft for smaller cargo, followed later by a new-design military airlifter is the most cost-effective option.
- Keeping the C-17A line open at low production rates to reduce future research, development, test, and evaluation expenditures is not cost-effective and does not produce smooth spending profiles.
- A C-17A SLEP to extend the life from 45,000 to 60,000 EFH could be cost-effective.
- RERPing the C-5s, in particular the C-5B, is cost-effective. It may also be cost-effective to RERP a portion of the C-5A fleet.

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Abbreviations

AFPAM	Air Force pamphlet
APOD	aerial point of debarkation
APOE	aerial point of embarkation
BW	basic weight
BWB	blended-wing body
CER	cost-estimating relationship
CFL	critical field length
C-X	notional new cargo aircraft
EADS	European Aeronautic Defence and Space Company
EFH	equivalent flight hours
ETAR	Ramstein Air Base, Germany (ICAO code)
EW	empty weight
FH	flying hours
FY	fiscal year
ICAO	International Civil Aviation Organization
KCHS	Charleston Air Force Base, South Carolina (ICAO code)

KDOV	Dover Air Force, Delaware (ICAO code)
LAIRCM	large aircraft infrared countermeasures
LEMO	Moron Air Base, Spain (ICAO code)
MC	mission capable
MCRS-16	Mobility Capabilities and Requirements Study 2016
MFW	maximum fuel weight
MGTOW	maximum gross takeoff weight
NPVLCC	net present value life-cycle cost
O&S	operating and support
OEW	operational empty weight
PAF	Project AIR FORCE
PAX	passengers
R&D	research and development
RDT&E	research, development, test, and evaluation
RERP	Reliability Enhancement and Reengine Program
SF	severity factor
SLEP	service-life extension program
SME	subject-matter expert
STTO	start engine, taxi, takeoff
TAI	total aircraft inventory
TPFDD	time-phased force deployment data
UIAFMA	USAF Intratheater Aircraft Fleet Mix Analysis
USAF	U.S. Air Force

CHAPTER ONE

Introduction

As of 2012, the U.S. Air Force (USAF) intertheater airlift fleet consists of C-5s and C-17As. There are three versions of the C-5—the C-5A, C-5B, and C-5M—and as of 2010, there were 111 C-5 aircraft in the inventory.[1] The C-17A is still in production; as of June 30, 2010, there were 192 C-17As in the inventory.[2] The 2010 USAF plan calls for C-17A production to cease in 2012 with a total inventory of 221 aircraft.

The work documented here was undertaken because much of the strategic airlift fleet will be reaching the end of its service life in the next few decades and because of concerns about the fleet and the potential need to devote considerable budgetary resources to maintain capability. Because of overseas contingency operations, C-17As have flown significantly more in the decade since September 11, 2001. The availability of the C-5s—especially the C-5As—has been an ongoing and significant problem affecting capability of the airlift fleet.

In future years, the aging of the fleet will mean that recapitalization actions will have to be taken. One option is development and procurement of a new military airlifter. This, however, requires a large capital outlay for research and development (R&D) and early produc-

[1] Two C-5Cs special mission aircraft were also produced as part of the C-5A production run. These aircraft are operationally similar to the C-5As and were considered to be C-5As before being RERPed and C-5Ms after being RERPed in this analysis.

[2] The production data we used in this study were current as of June 30, 2010. Less than a month later, a C-17A crashed while rehearsing for an air show (tail number 00-173, July 29, 2010). This aircraft was removed from our calculations.

tion units. Air Force budget realities make funding a large new aircraft procurement program very challenging. Other approaches may provide required capabilities without the kinds of spending peaks associated with new aircraft development.

We examined a broad range of potential aircraft alternatives and considered several permutations of USAF plans to provide an analytical foundation for making this important fleet recapitalization decision. The alternatives included commercial-derivative aircraft, new-design military airlifters, foreign military aircraft, and service-life extension programs (SLEPs) of the C-17A. We examined these alternatives using several potential fleet retirement schedules and changes to the USAF plan. These baseline permutations provide insight into a variety of situations, allowing USAF to understand the implications of choosing specific acquisition paths and to hedge against unexpected issues that may change the retirement schedule of the fleet. These were analyzed in terms of both net present value life-cycle cost (NPVLCC) and annual funding profiles.

The methodology for this analysis was broadly similar to that for past recapitalization studies RAND Project AIR FORCE conducted for USAF.[3] This methodology had four major elements:

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[3] We first evaluated options to recapitalize USAF's aerial refueling aircraft in the KC-135 Recapitalization Analysis of Alternatives (AoA), completed in early 2006. The results of that study were that the total cost of maintaining aerial refueling capability is insensitive to the timing of recapitalization and that, therefore, decisions about that timing should be made on other grounds, such as technical risk, some extra capabilities associated with new tankers, and the tightness of the overall U.S. Department of Defense budget in different times. See Michael Kennedy, Laura H. Baldwin, Michael Boito, Katherine M. Calef, James S. Chow, Joan Cornuet, Mel Eisman, Chris Fitzmartin, Jean R. Gebman, Elham Ghashghai, Jeff Hagen, Thomas Hamilton, Gregory G. Hildebrandt, Yool Kim, Robert S. Leonard, Rosalind Lewis, Elvira N. Loredo, Daniel M. Norton, David T. Orletsky, Harold Scott Perdue, Raymond A. Pyles, Timothy L. Ramey, Charles Robert Roll, Jr., William Stanley, John Stillion, Fred Timson, and John Tonkinson, *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Summary Report*, Santa Monica, Calif.: RAND Corporation, MG-455-AF, December 2005, Not available to the general public; and Michael Kennedy, Laura H. Baldwin, Michael Boito, Katherine M. Calef, James S. Chow, Joan Cornuet, Mel Eisman, Chris Fitzmartin, Jean R. Gebman, Elham Ghashghai, Jeff Hagen, Thomas Hamilton, Gregory G. Hildebrandt, Yool Kim, Robert S. Leonard, Rosalind Lewis, Elvira N. Loredo, Daniel M. Norton, David T. Orletsky, Harold Scott Perdue, Raymond A. Pyles, Timothy L. Ramey, Charles Robert Roll, Jr., William Stanley, John Stillion, Fred Timson, and John Tonkinson,

- determining the retirement profile of the fleet
- for each aircraft alternative or combination of alternatives, determining the number of aircraft required to meet the strategic airlift requirement
- determining the yearly procurement for each alternative to meet the overall requirement based on the retirement profile
- costing each fleet for each retirement profile.

Each of these will be discussed in significant detail later in this document.

This analysis used the requirement for strategic airlift defined in the Mobility Capabilities and Requirements Study 2016 (MCRS-16).[4] MCRS-16 presented several cases with different requirements. In consultation with the project sponsor, we used the strategic airlift requirement identified in "Case 1," which is the most stressing case for strategic airlift in MCRS-16.[5] In the Case 1 scenarios, U.S. forces conduct two nearly simultaneous large-scale land campaigns and respond to three nearly simultaneous homeland defense consequence-management events, with corresponding aerospace control levels and maritime awareness presence levels, that are concurrent with the land campaigns.

To adequately analyze the number of each aircraft alternative necessary to meet the MCRS-16 demand, we modeled the actual cargo moved. This produced a set of over 100,000 items shipped at various

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Analysis of Alternatives (AoA) for KC-135 Recapitalization: Executive Summary, Santa Monica, Calif.: RAND Corporation, MG-495-AF, 2006.

The second analysis was conducted as part of the USAF Intratheater Airlift Fleet Mix Analysis (UIAFMA), completed in late 2007. The results of that study were that conducting a SLEP on the combat-delivery C-130E and C-130H1 models is less cost-effective than replacing them with new C-130J-30s with equivalent capability. See Michael Kennedy, David T. Orletsky, Anthony D. Rosello, Sean Bednarz, Katherine Comanor, Paul Dreyer, Chris Fitzmartin, Ken Munson, William Stanley, and Fred Timson, *USAF Intratheater Airlift Fleet Mix Analysis*, Santa Monica, Calif.: RAND Corporation, MG-824-AF, October 2010, Not available to the general public.

4 U.S. Department of Defense and U.S. Transportation Command, "Mobility Capabilities and Requirements Study: Executive Summary," 2010

5 Office of the Secretary of Defense and U.S. Transportation Command, 2010, p. 3.

times during a war. This allowed us to differentiate between the types and amounts of different cargo that each alternative could carry. This was especially important, since not all aircraft alternatives could carry all cargo.

We identified and analyzed different alternative fleets to meet the requirement, producing both single-aircraft and mixed-aircraft fleets.[6] We compared these different fleets in terms of total NPVLCC. The fleet that meets the requirement at the lowest cost is the most cost-effective alternative. In addition to NPVLCC, we computed funding profiles for each year in the analysis. In some instances, large spikes in yearly spending may not be acceptable. For these, we considered cases that could smooth the funding profile and then determined how these affected NPVLCC.

Organization of This Document

This document is organized into seven chapters. Chapter Two presents our analysis of the retirement schedule for the fleet. Chapter Three discusses the aircraft alternatives we considered. Chapter Four presents the effectiveness methodology and results. Chapter Five discusses how the cost analysis was done for each aircraft alternative. Chapter Six presents the results of the cost-effectiveness and funding profile analysis, and Chapter Seven lays out our conclusions from this work. In addition, there are four appendixes. Appendix A illustrates an exemplar effectiveness calculation; in particular, it shows the handling of overlapping delivery windows. Appendix B details the calculation of aircraft flight times. A companion volume contains Appendixes C and D, which are not available to the general public.[7] Appendix C compares

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6 Mixed aircraft fleets were required since some aircraft alternatives could not carry all the cargo and therefore had to be paired with another aircraft to meet the total requirement.

7 The companion volume to this report contains two additional appendixes. See Christopher A. Mouton, David T. Orletsky, Michael Kennedy, and Fred Timson, *Reducing Long-Term Costs While Preserving a Robust Strategic Airlift Fleet: Appendixes C and D*, Santa Monica, Calif.: RAND Corporation, MG-1238/1-AF, forthcoming, Not available to the general public.

the characteristics of the alternatives included in the study. Appendix D presents an analysis of the MCRS-16 log file and characterizes the cargo demand.

CHAPTER TWO

Intertheater Airlift Fleet and Retirement Schedule

As of 2012, the USAF intertheater airlift fleet consists of the C-5 and the C-17A.[1] There are a total of 111 C-5s in the USAF inventory and by 2012, 221 C-17As are planned.

There are three versions of the C-5. As of 2010, the oldest version is the C-5A, which was in production from the late 1960s to early 1970s, of which 59 are in the current USAF inventory. The C-5B was produced during the mid- to late 1980s, and 42 are in the current Air Force inventory. The two C-5C special-mission aircraft were built during the early part of the C-5A production run. For our purposes, we considered these aircraft identical to C-5As.

The Reliability Enhancement and Reengine Program (RERP) is an ongoing modernization program for the C-5 series to upgrade avionics, engines, and other components. After an aircraft undergoes this upgrade program, it is designated a C-5M. As of fall 2010, one C-5A and seven C-5Bs had undergone this upgrade and are now designated C-5Ms. A RERP is not a SLEP and does not affect the service life of the aircraft. As of 2010, USAF planned to implement the RERP upgrade on all the C-5Bs but is retiring 22 of the C-5As. The resulting fleet will consist of 37 C-5As and 52 C-5Ms (one of which is an upgraded C-5A, two of which are upgraded C-5Cs, and the rest are upgraded C-5Bs). After retirement of the 22 C-5As, the fleet will still be capable of meet-

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[1] The aircraft inventory numbers here were current as of fall 2010. Later in this chapter, we present estimates of aircraft retirements based on usage. These estimates were based on data current as of October 26, 2010 for the C-5, and June 30, 2010 for the C-17A. We keep all numbers consistent with this mid- to late 2010 time frame.

ing the MCRS-16 Case 1 demand. The choice to retire these 22 C-5As was driven specifically by the excess capacity identified in MCRS-16 and the low availability of the C-5A in particular.

The National Defense Authorization Act for Fiscal Year 2012 authorized retirement of additional aircraft to decrease the C-5A fleet to 27, and the President's Budget for Fiscal Year 2013 is seeking to retire all C-5As. In light of these developments and the ongoing debate, we did a sensitivity analysis to look at this issue. We found that the results presented in the document are not sensitive to C-5A retirements, and the overall conclusions are independent of the retirements.

The C-17A is currently in production, with a total planned USAF inventory of 221 aircraft by the end of 2012. At this point, the Air Force does not plan to procure any additional C-17As. It is expected that the C-17A line will close shortly after USAF ceases procurement, with perhaps the Indian Air Force receiving the last deliveries in 2014.[2]

Projected Airlift Retirements

We projected a retirement schedule for the fleet to determine when new aircraft would need to be added to retain the required capability. To do so, we used each aircraft's flight hours as of 2010, the average severity for each, and a projection of future hours and severity for every aircraft to determine when it would reach a life-limiting constraint. Life-limiting issues on these aircraft are associated with structural fatigue. The equivalent flight hours (EFH) are tracked for each aircraft.[3] For both the C-5 and the C-17A, tail-specific accounting of EFH for several components for each aircraft has been done, and USAF provided us the

[2] Boeing, "Boeing to Build 10 C-17 Airlifters for Indian Air Force," news release, Long Beach, Calif., June 15, 2011.

[3] EFH is a metric used to express the accumulation of fatigue damage in critical areas of an aircraft's structure. This in general will not be equal to actual flight hours, since the missions flown by the aircraft do not match the baseline set of missions the aircraft was initially designed for. Because EFH tracks actual accumulation of fatigue damage, different missions of equal length may have significantly different EFH associated with them.

data in tabular form.[4] Boeing has said that all C-17As have the same two potential structural problem areas: the aft fuselage and the upper wing skin.[5] Both are subject to fatigue cracking. Conversely, C-5s have multiple structural problem areas that can be life-limiting, depending on the aircraft and its history. These include the upper aft crown, the inner wing upper, the inner wing lower, the outer wing upper, the outer wing lower, the horizontal tail, and the vertical tail. In addition, C-5s also have a pressure cycle limit. Each of these components is tracked for the C-5 fleet, and each aircraft has a specific component identified as its life limiter.

C-17A

The fatigue problem in the aft fuselage of the C-17A is of modest concern. Both USAF's Aeronautical Systems Center and Boeing believe that this problem is manageable and will require a minimal fix that should not significantly affect the life of the system. Boeing has done the preliminary engineering on the fix, which involves cold working of the rivet holes and other fairly well-understood procedures. Although Boeing has not yet done the cost analysis on this fix; the risk and cost may be low.

The upper wing skin is considered the life-limiting component of the C-17A. Several components on this aircraft are tracked, and all components that would require intensive and costly repairs have significantly more service life remaining than the upper wing skin does. As of 2010, the limit for the upper wing skin is 45,000 EFH.[6]

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4 Two Air Force Materiel Command organizations supplied EFH data to us: Aeronautical Systems Center's C-17 Engineering Branch provided EFH for each tail and other relevant information on the C-17A fleet (EFH data current as of June 30, 2010); and Warner Robins Air Logistics Center provided EFH data for each tail and other relevant information on the C-5 fleet (EFH data current as of October 26, 2010).

5 Ko-Wei Liu, "C-17 Aircraft Structural Integrity Program Overview," briefing, Boeing, November 2010

6 Conversations with Boeing engineers indicate that the aircraft may be able to safely fly past 45,000 EFH. The 45,000 EFH limit was based on component testing. The upper wing skin did not exhibit large-scale cracking at 90,000 EFH at the end of the test. For safety reasons and to account for differences between test and real-world operations, it is standard

To determine, for each aircraft, the number of years remaining before the upper wing skin reaches 45,000 EFH, we projected the average EFH accumulation into the future. To do this, we analyzed the historical pattern of how each aircraft was flown over its service life. Figure 2.1 shows the actual flight hours and the average severity factor (SF) for each aircraft in the inventory, based on its age.[7] The figure is broken up into two groups, the younger aircraft (those delivered after 9/11) and the older aircraft (those delivered before 9/11).

It is clear from this figure that the aircraft have been flown differently before and after 9/11. After 9/11, the aircraft tended to provide strategic airlift. As a result, the average number of hours flown went up (as indicated by the steeper blue slope on the left), but these hours, on average, were easier on the airframe (as indicated by the lower red values on the left). Prior to 9/11, training took up a larger proportion of the flying hours, which produces more fatigue damage per hour.

In interpreting Figure 2.1, it is important to note that all aircraft delivered after 9/11 flew exclusively in a post-9/11 world and that aircraft delivered before 9/11 flew in both a pre-9/11 and a post-9/11 world. The slope of the gray lines for actual flight hours indicates the average rate of flight hour accumulation both before and after 9/11. The SF fit is more complex because it is weighted based on whether the hours were flown before or after 9/11, which in turn is based on the age of the aircraft. A simple way to understand this chart is to consider two aircraft, one delivered right before 9/11 and one delivered right after 9/11. As the figure shows, since both of these aircraft flew almost entirely and exclusively in the post-9/11 world, they would have similar total flight hours and similar SFs. Older aircraft would, then, have more flight hours but would have accumulated them at a slower rate

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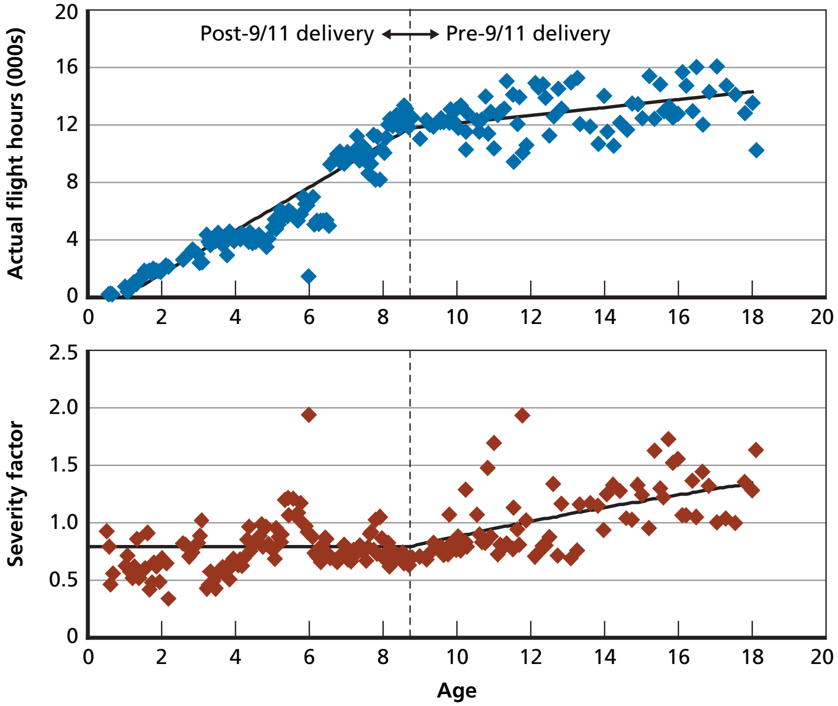
practice to set the operational life limit to 50 percent of the number of hours at which cracks are observed in tests. Since cracking was not observed at test completion, it is likely that the aircraft could safely fly beyond 45,000 EFH. Further component testing of the upper wing skin would be required to determine the actual level.

[7] SF is defined as the EFH divided by the actual flight hours and indicates the fatigue damage relative to the baseline. SF is often discussed on a per sortie basis.

Figure 2.1
Actual Flight Hours, Average Severity Factor, and Average Age for C-17As in the Inventory



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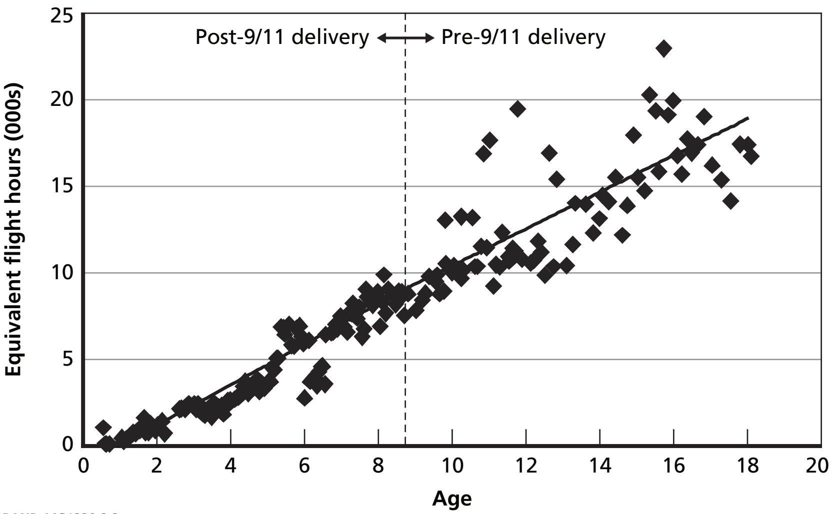
and would have higher SFs because they had spent more of their life in high-SF flying.

Multiplying the actual flight hours by the average SF for each aircraft gives the EFH for each aircraft. Figure 2.2 shows the EFH and age for each C-17A in the inventory. Note that there is a slight difference in the average yearly accumulation of EFH before and after 9/11, but the difference is not as large as one might have concluded looking at Figure 2.1. For each aircraft delivered after 9/11, we computed an average EFH accumulation rate of 1,165 per year. Using this number and assuming that the aircraft in the fleet before 9/11 were flown at this rate after 9/11, we computed an average EFH pre-9/11 accumulation

Figure 2.2
Equivalent Flight Hours and Aircraft Age for All C-17As



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rate of 1,056 EFH per year. After 9/11, the C-17As EFH accumulation increased by 11 percent per year over that before 9/11.

Since projections of EFH accumulation drive the retirement date of the aircraft, we looked at two additional cases to arrive at our estimated accumulation rate. Both cases started with the Air Force projection of 1,085 flight hours per aircraft per year. We first computed a weighted fleetwide SF average using the historical data presented in Figure 2.1. This SF was 0.92, resulting in an accumulation rate of 1,000 EFH per year—slightly less than our pre- and post-9/11 analysis presented in Figures 2.1 and 2.2 and representing an average over the life of the fleet. The second again used the 1,085 projected flight hours, but this time using the weighted average SF for post-9/11 flying, 0.77. This resulted in an accumulation rate of 835 EFH per aircraft per year. The rationale for the second case was that, while the number of flight hours may decrease as commitments to the Global War on Terror decrease, the types of hours would remain about the same as they are today. These two cases, in addition to the post-9/11 EFH accumulation rate through 2010 of 1,165 EFH per year, provided a good range of

possible future EFH accumulation (1,000; 835; and 1,165, respectively) on which to base our analysis. We carried 1,000 EFH per year forward as the baseline for our analysis and ran sensitivity cases of ±20 percent to account for these potential variations. These analyses are presented in Chapter Six.

C-5

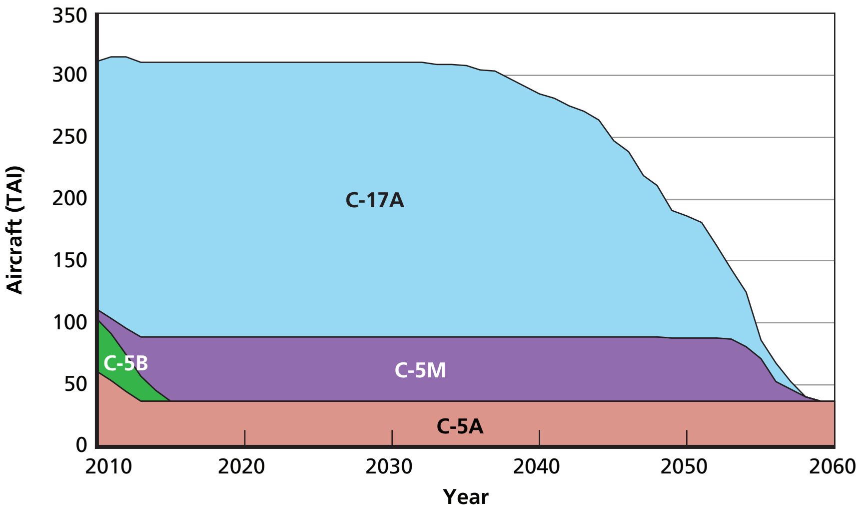
The C-5 fleet has several components that could be the limiting factor. Because of this, it is not possible to discuss a single EFH accumulation for the aircraft; rather, EFH makes sense only relative to a particular component. This is in contrast to the C-17A, which has only one life-limiting component, which means that the EFH for that C-17A component can be thought of as the EFH for the C-17A itself. Therefore, while this section will discuss the C-5 only in terms of actual flight hours, the results presented here are based on calculations for the EFH on each component of each tail.

For each C-5 in the inventory, eight component issues are tracked to determine which will be the life limiter and when the aircraft will need to be grounded (or flight restrictions imposed), based on the flight limits. USAF tracks the equivalent hours for each of the eight potential life-limiting components for each aircraft. To compute the remaining service life for each C-5, we used the Air Force projected flying hours (FH) for each aircraft model (305 for the C-5A, 580 for the C-5B, and 580 for the C-5M) and a weighted average SF for each of the eight potential life-limiting components to determine an EFH accumulation for each of these components. Combining this projected accumulation rate with the airframe-specific accumulated EFH per component, we then determined the specific life-limiting component for each aircraft and the expected number of years remaining.

Fleet Drawdown

For both the C-5 and C-17A, we used these projections of remaining years of life for each airframe to determine the number of retirements due to structural fatigue issues that could be expected each year. Figure 2.3 shows the projected retirement profile for the fleet. These retirement profiles are based on 305 FH/year for the C-5A;

Figure 2.3
Projected Retirement Profile of Fleet



RAND *MG1238-2.3*

580 FH/year for the C-5B and C-5M; and 1,085 FH/year for the C-17A. Since many different C-5 components are being tracked, each with a different SF, no single value for EFH/year can be used for the C-5. However, since the C-17A is limited by only one component, which is estimated to have an SF of 0.92, it accrues 1,000 EFH/year

The Air Force plans to convert all C-5Bs to C-5Ms by 2015 and to retire 22 C-5As by 2014. This is shown in Figure 2.3. The figure also shows that the C-17As are the first aircraft to reach their life limit, starting in the mid-2030s. Although these aircraft are newer than the C-5s, they are being flown many more hours per year and are accumulating EFH at a much higher rate. The drawdown of the C-17As occurs over a period of about 20 years—very similar to its production time line (1992–2011). In the mid-2050s, the C-5Ms will begin to reach their life limit and will be retired near the end of the drawdown of the C-17A fleet. Since the C-5As are being flown a small number of hours

per year, these aircraft will not reach their structural-life limit for many years.[8]

The analysis presented later in this document used the fleet drawdown curve presented in Figure 2.3 as the baseline retirement schedule for the fleet. Permutations of this schedule were used to explore different cases to understand how the answer might change under different circumstances and to understand the robustness of the answers.

Reduced Force Levels—Budget Control Act of 2011

After the completion of this study, the U.S. Congress enacted the Budget Control Act of 2011. Among other things, this caused a shift in national security strategy to reflect a reduced budget. The National Defense Authorization Act for Fiscal Year 2012, signed into law on December 31, 2011, allowed the retirement of additional C-5As beyond the planned retirements we considered. In particular, the act approved a reduction to 27 C-5As. It was reported in March 2012 that the Air Force was requesting from Congress the authority to retire all the remaining C-5As. The justification for this request was based on strategic guidance that no longer required the military to fight two near-simultaneous large-scale land wars.[9] This previous requirement aligned with MCRS-16 Case 1, the case we used; however, the new strategic guidance better aligns itself with a different case.

It is important to note that the results from the baseline case in this study are still relevant and that the relative savings among alternatives should remain nearly unchanged. This is because the C-5A fleet gives a constant level of capability through 2078. Reducing the requirement by an amount equal to the C-5A capability and removing the C-5As does not affect the rest of the fleet until 2079, at which time discounting makes these changes small. This concept is illustrated in Figure 2.4.

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[8] Figure 2.3 shows only life limits that are due to structural fatigue issues. It is likely that the C-5A will be retired for a reason other than structural fatigue at some point prior to reaching this limit—unless upgrades are done and, as a result, the C-5A begins to fly significantly more hours.

[9] U.S. Air Force, "USAF Force Structure Changes: Sustaining Readiness and Modernizing the Total Force," March 2012.

Figure 2.4
Similarity Between Baseline Case and Reduced Requirement Case

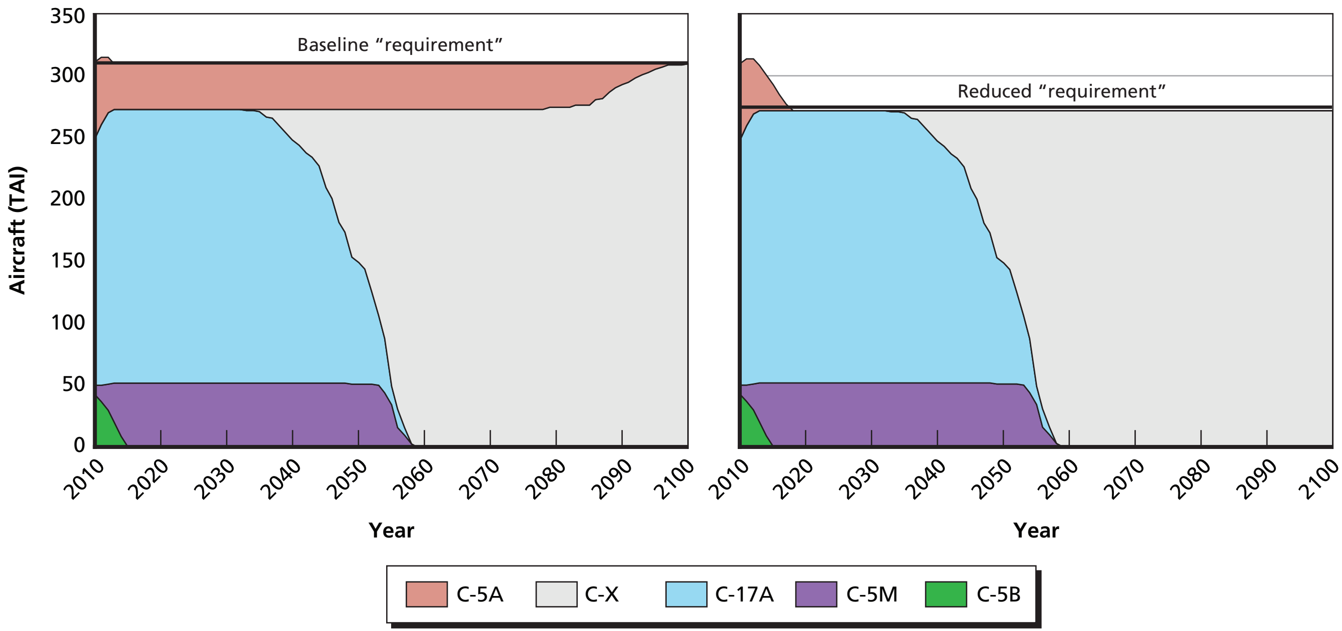

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Figure 2.4 illustrates that, given a reduced requirement and early C-5A retirement, the cost for all other aircraft (C-5M, C-17A, and any C-X alternative) does not change until 2079. Starting in 2079, the difference between the C-X procurement in the two cases is small and, when discounted, represents little real change. Therefore, the cost differences between future fleet alternatives in the baseline case are applicable to a reduced force structure case. Also note that, in Figure 2.4, the word *requirement* is in quotes to highlight the fact that the actual analysis defines the requirement not as a tail count, but rather as a fleet capability. For illustrative purposes, however, a tail requirement is sufficient.

Options Considered for the C-5 and C-17A Fleets

There are eight options considered for the fleet. These options are:

- baseline
- continue C-17A production
- partially RERP C-5A
- retire C-5A in the near term
- limited C-5B RERP
- retire C-5A starting in 2030
- retire all C-5 starting in 2030
- retire C-5A starting in 2060.

Although not expected to produce net present value savings, two options were considered for their possible ability to smooth the spending profile by removing the need for a new research, development, test, and evaluation (RDT&E) program in the future:

- low-rate C-17A production (two per year)
- low-rate C-17A production (six per year).

The first eight of these fleet options can be followed by any aircraft alternative. The last two of these current-fleet options make sense only when followed by high-rate C-17A production. Nothing other

than a C-17A can follow these options because one of the main reasons to keep the C-17A line open at a low rate is to be able to avoid a large RDT&E when high-rate production is needed. We assumed that all C-5B/C RERPs and planned C-17A procurement will be complete by 2014.

The **baseline** option is very similar to the 2010 USAF plans and specifically calls for RERPing all C-5B aircraft, retiring all but 41 C-5A aircraft,[10] and halting C-17A production once at 221 aircraft. This option does not produce a shortfall in military capability until 2033.

The **continue C-17A production** option calls for the baseline but continues C-17A aircraft procurement at a rate of ten per year starting in 2015, for a total additional procurement of 41. In addition, starting in 2015, ten C-5A aircraft are retired per year. This option does not produce a shortfall in military capability until 2033.

The **partially RERP C-5A** option calls for the baseline and, in addition, the RERP of 21 C-5A aircraft and the retirement of 20 C-5A aircraft. Because a C-5M has approximately twice the availability of a C-5A, one C-5M has approximately the same military capability as two C-5As. This option does not produce a shortfall in military capability until 2033.

The **retire C-5A in the near term** option calls for the baseline but begins to retire all C-5As in 2015, at a rate of ten per year.[11] This option produces a shortfall in military capability in 2015, which necessitates the near-term procurement of a new aircraft alternative.

The **limited C-5B RERP** option modifies the baseline by only RERPing a total of 29 C-5B/C and retaining 23 C-5B and 52 C-5A aircraft. This option does not produce a shortfall in military capability until 2033.

The **retire C-5A starting in 2030** option modifies the baseline by retiring C-5A aircraft before the end of their structural life. Starting in 2030, ten C-5A aircraft are retired per year. This option produces

10 The 2010 USAF plan calls for 37 C-5A aircraft.

11 The cost for this option assumes a C-17A production rate of 15 per year, with five international sales per year in addition to ten USAF buys per year.

a shortfall in military capability in 2030. This option recapitalizes C-5A aircraft immediately before the recapitalization of C-17A aircraft begins in 2033.

The **retire all C-5 starting in 2030** option modifies the limited C-5B RERP option by retiring all C-5 aircraft before the end of their structural life. Starting in 2030, ten C-5 aircraft are retired per year, starting with C-5A aircraft, followed by C-5B aircraft, followed by C-5M aircraft. This option produces a shortfall in military capability in 2030. Since this option retires the C-5Ms before the end of their structural life, the C-5B/C RERPs were limited.

The **retire C-5A starting in 2060** option starts the C-5A retirement 30 years later than the previous option. This puts the recapitalization of C-5A aircraft at the end of the recapitalization of C-17A aircraft, which began in 2033. This option does not produce a shortfall in military capability until 2033.

The **low-rate C-17A production (two per year)** option modifies the baseline by continuing C-17A production past the planned 221 aircraft at a rate of two per year from 2015 through 2034.[12] For each C-17A aircraft procured, one C-5A is retired. This option is only considered in the context of being followed by high-rate C-17A production.

The **low-rate C-17A production (six per year)** option modifies the low-rate C-17A production (two per year) by increasing the low-rate production from two aircraft per year to six aircraft per year.[13] Initially, for each C-17A aircraft procured, one C-5A is retired until all C-5As are retired; then for every three C-17A aircraft procured, two C-5B are retired until all C-5Bs are retired; then for every two C-17A aircraft procured, one C-5M is retired. As with the low-rate C-17A production (two per year) option, this option is considered only in the context of being followed by high-rate C-17A production.

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[12] The cost for this option assumes a total production rate of two per year, which means there are no international sales.

[13] The cost for this option assumes a total production rate of six per year, which means there are no international sales.

CHAPTER THREE

Aircraft Alternatives

We considered 15 aircraft alternatives. These formed the basis for both single- and mixed-fleet options. These alternatives represent a broad spectrum of aircraft types, including C-5 and C-17A, C-17A derivative aircraft, foreign military aircraft, commercial-derivative aircraft, and future-design aircraft incorporating a range of technology options.

Aircraft Alternatives Analyzed

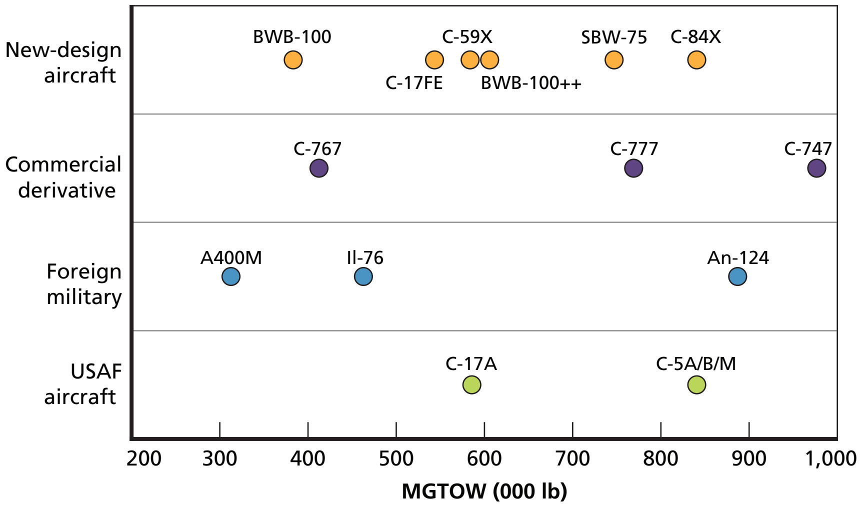
Figure 3.1 summarizes the aircraft alternatives considered.

It is important to note that, other than the C-5 and C-17A, the aircraft used in this analysis are simply representative and may not be available at the time an actual procurement decision is made. For example, if a commercial-derivative option is chosen in the 2030 time frame, many of these aircraft will be out of production, and others we have not considered will likely be in production. These aircraft can therefore be thought of as representative of various aircraft classes.

C-5 and C-17A Aircraft

These are the C-5A/B, C-5M, and C-17A. For the purposes of effectiveness analysis, the C-5A and C-5B have the same flight characteristics, even though their availabilities are different. We assumed that a C-5C aircraft has the same capabilities and performance as a C-5A aircraft before a RERP and a C-5M aircraft after a RERP.

Figure 3.1
Summary of Aircraft Alternatives



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A C-17A–Derivative Aircraft

The C-17FE is essentially a narrow-body C-17A. Besides the increased fuel efficiency of the C-17FE, the C-17FE was also designed to increase access to short and soft fields. Since the requirements we used here did not include operations out of short and soft fields, the C-17FE did not receive credit for this capability in our analysis. The C-17FE did, however, have a lower RDT&E cost because of its commonality with C-17A.

Commercial-Derivative Freight Aircraft

These are the Boeing 767-300F, the Boeing 777, and the Boeing 747-8F, which we designated as the C-767, C-777, and C-747, respectively, for this analysis. The purpose of this designation is to highlight the fact that these are militarized commercial freighters. When computing the empty weights of these aircraft, we made allowances for military equipment, such as large aircraft infrared countermeasures, missile warning receivers, and chaff and flares.

Foreign Military Aircraft

These are the European Aeronautic Defence and Space Company (EADS) A400M, the Antonov An-124-100M-150, and the Ilyushin Il-76MF. The EADS A400M was the only turboprop aircraft we considered; traditionally, turboprop aircraft are not best suited for strategic airlift. The An-124-100M-150 is a commercial version of the An-124 fitted with Western avionics. The An-124-100M-150, which is most similar to the Lockheed C-5, had its first flight approximately 14 years after the C-5. The Il-76MF is a stretched variant of the Il-76 and most closely resembles the Boeing C-17A; however, the Il-76 first flew in 1971, 20 years before the C-17A. Here, we refer to the An-124-100M-150 simply as the An-124 and to the Il-76MF simply as the Il-76.

New Current-Technology Aircraft

To fully explore the design space, it was important to consider new-design aircraft that incorporate technologies ranging from current technology to the much more advanced BWB technology. To establish a baseline for these new-design, current-technology aircraft, RAND proposed the C-59X and the C-84X. These aircraft have the same performance, weight, and characteristics as the C-17A and C-5M, respectively. By using the same characteristics as the C-17A and C-5M, these aircraft incorporate current technology. However, for the purposes of costing, these aircraft were considered new designs. This means that a full R&D program that did not rely on heritage designs would need to be executed, and the learning curve would begin anew.

New Future-Design Aircraft

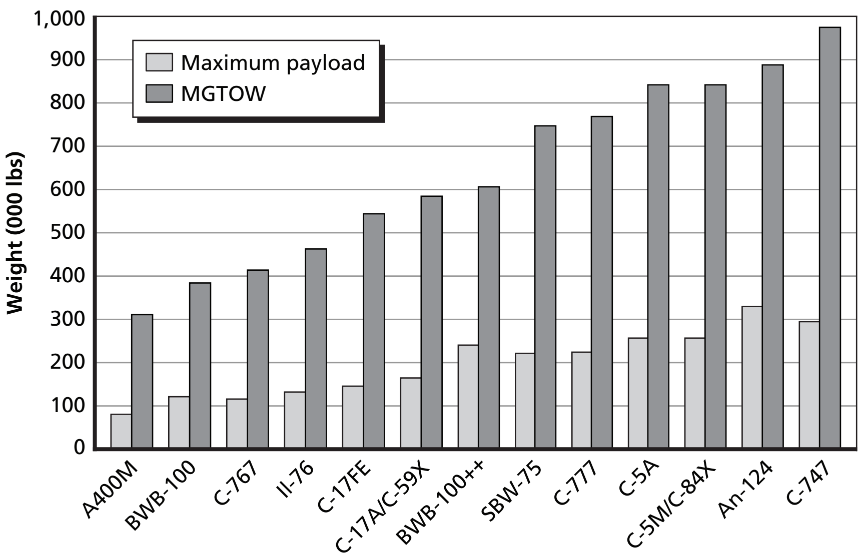
These included two blended wing body (BWB) options from Boeing, the BWB-100 and the BWB-100++. Both the BWB-100 and BWB-100++ have a great deal of part commonality. As a smaller aircraft, the BWB-100 is meant as a possible technology hedge before the development of the much larger BWB-100++. Starting in the late 1990s, NASA and Boeing began undertaking BWB technology research and have recently completed flights of the X-48. The X-48 program consisted of two 8.5-percent scale aircraft for flight testing to study the characteristics of BWB aircraft. The first flight of the X-48 was in July of 2007.

The third new future-design aircraft was the Lockheed SBW-75 box-wing aircraft. The SBW-75 is unique in that it has an adjustable floor that allows the aircraft to operate with one high main cabin or with the space split into upper and lower cabins. This analysis considered the deck configuration to be fixed, meaning that the fleet consisted of an optimum number of single-deck (SBW-75.1) and double-deck (SBW-75.2) configurations. We did not allow the deck configuration to vary on the assumption that the reconfiguration time would negate any benefit from the reconfiguration. As will be discussed later, these aircraft represent varying levels of technology. Boeing's BWB options represent a significant technological leap, while the Lockheed SBW-75 represents a more modest technological leap.

Aircraft Alternative Weight Characteristics

Figure 3.2 sorts the aircraft alternatives by maximum gross takeoff weight (MGTOW). The smallest aircraft, the A400M, has a MGTOW

Figure 3.2
Aircraft Alternative Weights and Payload



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of 310,851 lb; the largest aircraft, the C-747, has a MGTOW of 975,000 lb. The payloads also range widely across alternatives, from 81,570 lb for the A400M to 330,693 lb for the An-124.

To ensure proper weighting of each alternative aircraft considered, we devised a weight equalization procedure. In particular, the procedure started with the basic weight from each manufacturer for each aircraft, then modified that weight to ensure that all aircraft weights included the same equipment. These modifications took five specific items into account: large aircraft infrared countermeasures (LAIRCM), missile warning receiver, chaff and flare dispenser system, load master station, and sidewall seating.

Table 3.1 shows, for each alternative, the equipment that needed to be added to calculate the modified basic weight. Note that the basic weights of the C-5 and C-17A, already include all the necessary equip-

Table 3.1
Equipment Addition to Aircraft Basic Weight

Aircraft	LAIRCM	Missile Warning Receiver	Chaff and Flare Dispenser System	Load Master Station	Sidewall Seating
A400M	X	X	X		
BWB-100	X	X	X	X	X
C-767	X	X	X	X	X
Il-76	X	X	X		
C-17FE					
C-17A / C-59X					
BWB-100++	X	X	X	X	X
SBW-75	X	X	X	X	
C-777	X	X	X	X	X
C-5A					
C-5M / C-84X					
An-124	X	X	X		X
C-747	X	X	X	X	X

ment. Commercial-derivative aircraft and both BWB aircraft required addition of all five items.

We assumed an empty weight for each aircraft of 99.43 percent of its basic weight.[1] Aircraft's operational empty weight (OEW) then added crew, cargo handling equipment, fixed equipment and armor, and chaff and flares. Appendix C offers further details on aircraft empty weight and OEW.[2]

Table 3.2 summarizes the weights for various components used in the equalization of both basic weight (BW) and OEW.

Table 3.2
Estimates Used for Weight Equalizations

Component	Weight Category	Details	Weight Estimate
LAIRCM	BW	3 SLTA; 6 AN/AAR-54 MAW; 1 control indicator; 1 processor; fairings, wiring, and mounting	500 lb
Missile warning receiver (MWR)	BW	1 AN/AAR-47 (1 CP; 6 OSCs; wiring and mounting)	100 lb
Chaff and flare dispenser system	BW	12 AN/ALE-47; 1 control unit; wiring and mounting	100 lb
Load master station	BW		500 lb
Sidewall seating	BW		12 lb/linear ft
Crew member	OEW	Passenger (PAX) and Kevlar blankets	250 lb
Cargo handling equipment	OEW		70 lb/pallet position[a]
Fixed equipment and armor	OEW		2,500 lb[a]
Chaff and flares	OEW	12 AN/ALE-47	265 lb

[a] Estimate based on regression of A400M, C 17A, and C 5 data.

[1] This assumes an average ratio between empty weight and basic weight for the C-767, C-17FE, and BWB-100++.

[2] Mouton et al., forthcoming.

Each aircraft has two officer positions: pilot and first officer. The C-5 and An-124 both require an enlisted flight engineer. We assumed that all aircraft require a load master and a scanner, and aircraft with 20 or more pallet positions require an additional enlisted person. Table 3.3 provides the crew makeup and pallet positions we used to calculate the OEW for each aircraft.

Aircraft Alternative Payload and Range Capability

For purposes of computing aircraft effectiveness, we modeled each aircraft through flight in detail. This included limits on takeoff and landing weights based on field length, field elevation, and temperature. For illustrative purposes, and to convey a general sense of aircraft capabil-

Table 3.3
Aircraft Crew and Pallet Positions

				Positions	
Aircraft	**Enlisted**	**Officer**	**Total Crew**	**Pallets**	**PAX**
A400M	2	2	4	9	54[a]
BWB-100	2	2	4	19	
C-767	3	2	5	26	
Il-76	2	2	4	13	
C-17FE	2	2	4	12	54[a]
C-17A / C-59X	2	2	4	18	
BWB-100++	3	2	5	38	
SBW-75	3	2	5	38	
C-777	3	2	5	30	
C-5A	4	2	6	36	73[b]
C-5M / C-84X	4	2	6	36	73[b]
An-124	4	2	6	38	88[b]
C-747	3	2	5	38	

[a] Available sidewall seating with full pallet loading.

[b] Upper-deck seating.

ity, Appendix C presents a payload-range curve for each alternative aircraft analyzed assuming takeoff and landing from sea level on a standard day with no runway length constraints.[3]

Mission-Capable Rates

We based our effectiveness analysis on mission-capable (MC) aircraft; however, costing the fleet required calculating the total aircraft inventory (TAI). The required TAI is estimated to be the number of MC aircraft divided by the availability rate.[4] The *availability rate* is defined as the percentage of aircraft that are command possessed (i.e., that are not depot possessed) times the percentage of these aircraft that are mission capable. The MC rate, depot-possessed rate, and net availability for each aircraft analyzed are shown in Table 3.4.

Measures of Aircraft Technology Risk

As discussed earlier, this study looks at aircraft with a variety of technological enhancements. These range from the current-technology C-59X and C-84X to the highly advanced BWB-100++. While technology advancements have associated cost savings, they also mean taking on significant additional risk. Appendix C presents the details of this analysis.[5] The BWB presented the greatest technological risk, which was due to its low empty weight fraction and high use of composites. The SBW-75 presented a medium technological risk that was due to its use of composites and the novel wing design. We consider technical risk later in this document, under conclusions and recommendations.

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[3] Mouton et al., forthcoming.

[4] Note that the exact calculation of TAI depends on the desired confidence level that cargo will be delivered on time. This would require a Monte Carlo simulation because, on days when more than the required number of aircraft are mission capable, it may be possible to deliver cargo earlier than originally planned. Conversely, on days when fewer aircraft are mission capable than expected, there may or may not be a delay depending on whether or not some cargo was flown earlier than planned.

[5] Mouton et al., forthcoming.

Table 3.4
Net Availability of Alternative Aircraft (percent)

Aircraft	Mission Capable Rate	Depot Possessed	Net Availability
C-17A	85	14	73
C-5A	53	38	33
C-5B	61	19	49
C-5M	75	14	65
All other	85	14	73

CHAPTER FOUR

Effectiveness Methodology and Results

Overview

The effectiveness analysis followed these general steps for each alternative aircraft:

- **Analyze cargo demand based on aircraft capability**. MCRS-16 cargo was divided into two groups, the cargo that could fit on the alternative (generically denoted C-X) and the cargo that could not fit. For the cargo that could fit, each piece was converted into C-X equivalent pallets.
- **Compute mission and route requirements**. Each C-X was "loaded" with the cargo, subject to the delivery time and location requirements, to determine the number of missions C-X would need to fly each day of the war to deliver all the C-X compatible cargo. This also produced the number of missions that were flown on each route, where a route is an aerial point of embarkation–aerial point of debarkation (APOE-APOD) combination.
- **Compute mission times**. The C-X mission time was computed based on a weighted average of the mission time for each route between the APOE and the APOD. The mission time is the sum of aircraft ground time and aircraft flight time.
- **Compute fleet size and relative aircraft effectiveness**. Knowing the number of missions that need to be flown along with the weighted average mission time, we calculated the number of MC aircraft required to meet the delivery requirements. The relative effectiveness of each alternative was then the ratio of the number

of MC C-5Ms required to deliver the C-X compatible cargo and the number of MC alternative aircraft required to deliver the same cargo. In addition, the capability of the C-X to carry all the cargo is defined by the number of MC C-5Ms required to deliver everything that does not fit on the alternative.[1]

The above steps are completed for each aircraft alternative (C-X) and the C-5 and C-17A.

Analyze Cargo Demand Based on Aircraft Capability

The demand against which we measured each aircraft alternative was based on MCRS-16 Case 1 time-phased force deployment data (TPFDD) or, more specifically, the MCRS-16 air movement "log file."[2] This log file is generically referred to as the TPFDD; however, some important differences between the TPFDD and the log file exist.[3] Some of these specific differences include the latest delivery data. Where the TPFDD had delivery dates that were near impossible to meet, the MCRS-16 log file incorporated subject-matter expert (SME) judgment in pushing back some of these dates. In addition, the MCRS-16 log file included cargo that needed to be transported but that did not have data at the TPFDD level. Importantly, the log file separated cargo based on

[1] Note that the C-5M is being used as a unit of measure. That is to say, the amount of non-C-X compatible cargo is expressed in terms of the number of C-5Ms, not that the cargo needs to fly on a C-5M. The cargo can, in fact, fly on any aircraft that is capable of carrying it.

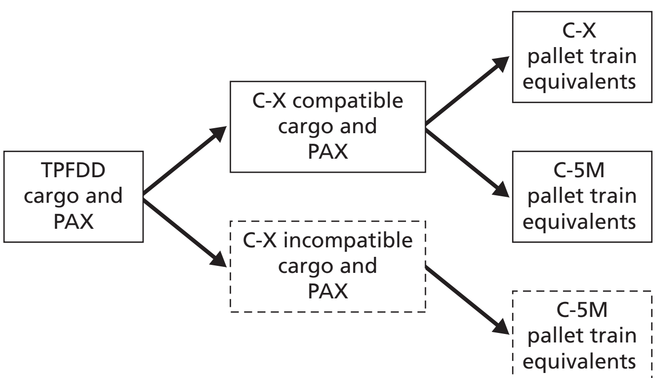
[2] This file contained information on all air movements executed in the MCRS-16 requirements study. In particular, the log file contained data on each individual piece of cargo, including its weight and dimensions. Some log file lines did not contain details for individual cargo items; in such cases, representative cargo items were used. In aggregate, these representative cargo items mirrored the known cargo items. Some of the log file data, such as when cargo items were loaded and unloaded or the type of aircraft the cargo flew on, were not used. We used the MCRS-16 log file only to obtain the demand, specifically what needed to be moved, when it needed to be moved, and where it needed to be moved.

[3] Although the TPFDD and the log file are not identical, we use *TPFDD* to capture the level at which we analyzed the data.

whether it flew on Civil Reserve Air Fleet or USAF organic aircraft. This separation allowed us to only look at the organic airlift demand, which is important, given the significant role of the Civil Reserve Air Fleet. The log file also contained data on the earliest and latest each piece of cargo could arrive, its dimensions and weight, and its origin and destination. For our purposes, the latest a cargo item could arrive was the later of the latest arrival date specified in the TPFDD or the actual MCRS-16 log file arrival date. In total, the log file consisted of over 100,000 individual cargo elements identified in the MCRS-16 requirements study.

Figure 4.1 illustrates this methodology graphically and shows that the TPFDD data, derived from the MCRS-16 log file, are broken up into two categories for each C-X. These categories are the cargo that can fit on the C-X, denoted "C-X Compatible Cargo and PAX," and the cargo that does not fit on the C-X, denoted "C-X Incompatible Cargo and PAX." All our alternatives are capable of carrying passengers (PAX), either in a separate seating compartment, on sidewall seating, or on palletized seating. Cargo is said to be C-X incompatible if its height is greater than the centerline pallet position height, if it is wider than the cabin width, or if it is longer than the maximum pallet train

Figure 4.1
Division of TPFDD Cargo and PAX



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capability of the aircraft. These two groups of cargo were then converted to 463L pallet equivalents.[4]

The C-X compatible cargo falls into one of two loading groups, either tandem or centerline. A cargo item has to go centerline if either it is taller than the tandem position height or it is wider than the tandem position width.[5] The number of pallet positions a cargo item is said to occupy, then, depends only on its length and whether or not it is in a tandem position. For cargo items in a tandem position, the number of pallet positions the item occupies is simply the length of the item divided by the length of a tandem pallet, rounded up. For a centerline position, the number of pallet positions the item occupies is the length of the item divided by the length of a centerline pallet,[6] rounded up, times the ratio of total tandem positions to total centerline positions. As an example, consider a cargo item that is 96 in. wide, 210 in. long, and 60 in. high on a C-5M. This item can fit tandem and would require three pallet positions (210 ÷ 88 = 2.39). Similarly, an item that is 150 in. wide, 210 in. long, and 60 in. high on a C-5M must go centerline. This means it would take three centerline positions, which, recalling that a C-5M has 36 tandem pallet positions but only 18 centerline positions, is six pallet positions (3 × 36 ÷ 18 = 6). The two loading examples are illustrated in Figure 4.2.

We converted the C-X compatible cargo to pallet equivalents for both C-X and the reference C-5M. This allowed us to compare the effectiveness of C-X against that of the C-5M at carrying the C-X compatible cargo; this will be the basis for the relative effectiveness of C-X. The C-X incompatible cargo is converted only to C-5M pallet equivalents, since it cannot fit on the C-X, but can fit on a C-5M;[7] this will

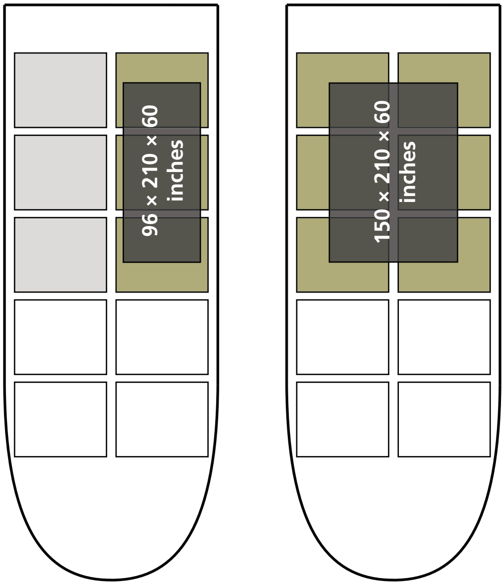
4 Some TPFDD items were much smaller than a pallet; therefore, when possible, we combined these items to create fuller pallets, which, on average, were 50 percent of the maximum pallet volume.

5 Some aircraft we examined place the tandem 463L pallets 108 in. wide, while others place the tandem 463L pallets 88 in. wide.

6 Centerline pallets are 108 in. wide and 88 in. long for all aircraft we examined.

7 MCRS-16 log file data were scrubbed to exclude any item that did not fit on both a C-17A and a C-5.

Figure 4.2
Example of Cargo Pallet Equivalents



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be the basis for determining the percentage of the fleet that must be an aircraft other than C-X that is capable of carrying all the cargo.

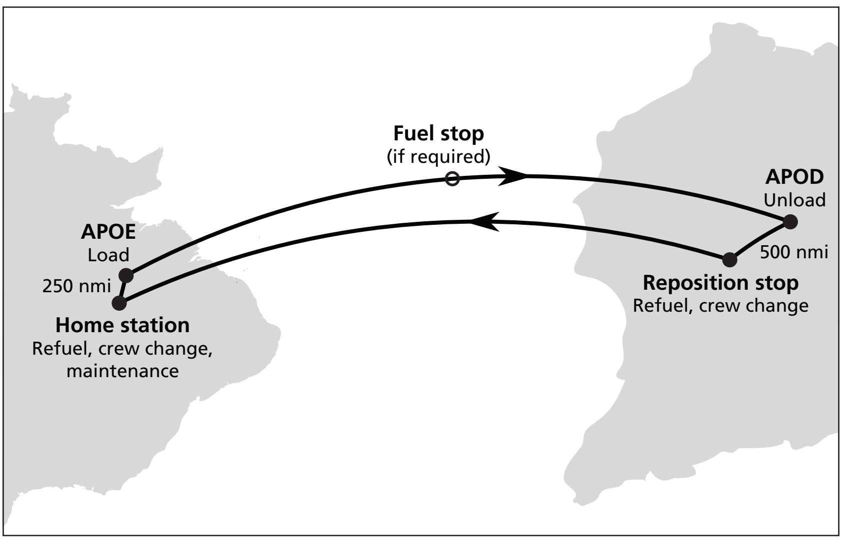
Compute Mission and Route Requirements

After expressing the TPFDD demand in terms of pallet train equivalents, which includes the timing and routing requirements, we could calculate the number of missions on each route. This demand can be expressed as delivery windows and requirement levels for each route. In addition, given the number of missions required on each route on each day, we could compute the total number of missions flown per route. Appendix A provides the details of the process for modeling the daily aircraft assignments, as well as an example.

Compute Mission Times

This methodology required the computation of the round trip mission time for each aircraft on each route. Each mission was divided up into four or more flight segments and an equal number of ground segments, depending on the distance of the route and the aircraft alternative's range with the required payload. The time and fuel burned during the flight segments were computed using a RAND-developed aircraft flight model. Ground times were computed using planning factors, which were based on those in Air Force Pamphlet (AFPAM) 10-1403.[8] Figure 4.3 illustrates the mission cycle. Each mission begins at the APOE, where the cargo is loaded. The flight to the APOD will make refueling stops as required, given the average payload per mis-

Figure 4.3
Mission Cycle Representation



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[8] Air Force Pamphlet (AFPAM) 10-1403, *Air Mobility Planning Factors*, Washington, D.C.: Department of the Air Force, December 18, 2003.

sion for that alternative aircraft.[9] The aircraft then spends time on the ground at the APOD, where the cargo is unloaded. After the unloading stop, the aircraft flies 500 nmi to the reposition stop.[10] The aircraft again spends on the ground at the reposition stop for refueling and crew changes. The aircraft then returns to the home station. It is assumed that the great circle distance from the reposition stop to the home station is the same as the great circle distance from the APOE to APOD. Since the aircraft is flying with no payload, it will be able to complete this leg with as many or fewer stops than the APOE to APOD trip took. At the home station, the crew is changed, the aircraft is refueled, and any necessary maintenance is done. Finally, the aircraft flies 250 nmi to the next APOE.[11]

We modeled each aircraft alternative throughout each phase of flight and ground operations, in particular, describing aircraft flight performance in terms of several key parameters. These included critical field length (CFL) and landing distance over a 50-foot obstacle as a function of aircraft weight, field altitude, and atmospheric temperature. These also included climb fuel burn, distance to climb, and time to climb as a function of initial altitude, final altitude, and initial weight. In addition, cruise was described by specific range at optimum altitude and optimum Mach number as a function of weight.[12]

Aircraft Ground Times

The model included two types of aircraft ground times. The first was a *productive stop*, for either loading or unloading. The second type was a *nonproductive stop*, for refueling. The time for productive stops was a

9 The average mission payload is defined by the total payload weight for the alternative aircraft divided by the number of missions required to deliver that payload.

10 This distance is based on AFPAM 10-1403 productivity factors for strategic flights.

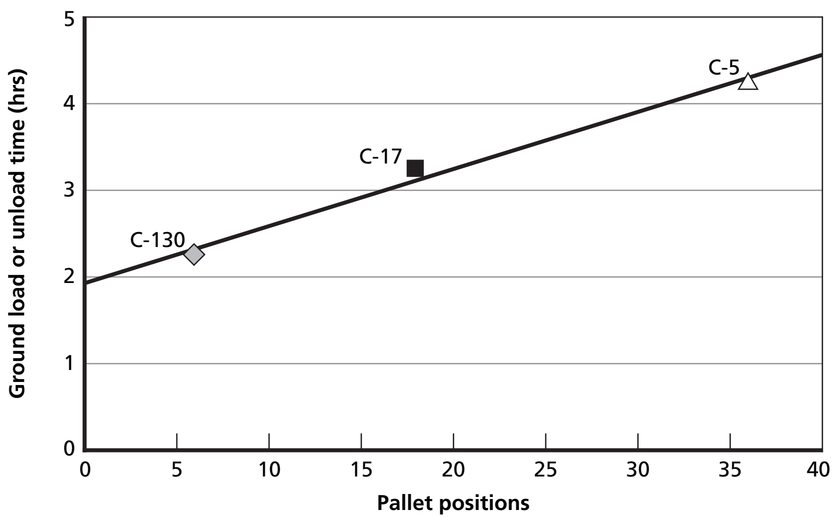
11 This distance is based on AFPAM 10-1403 productivity factors for tactical flights.

12 For computational efficiency, field constraints and climb were table lookups with appropriate interpolations. Cruise-specific range and optimum altitude were expressed as a quadratic equation in terms of aircraft weight. Expressing these quantities in terms of a quadratic allows direct calculation of the cruise fuel burn and cruise time through appropriate integration of the quadratic functions. Knowing the altitude and Mach number throughout cruise flight allows calculation of the speed throughout cruise flight.

function of the number of pallets; the time for nonproductive stops was a function of maximum fuel weight.[13] AFPAM 10-1403 gave ground times for several aircraft, but we used only the C-130, C-17A, and C-5 to form the regression. Figure 4.4 shows the linear data regression, which was the basis of all aircraft ground times in this analysis, rather than AFPAM 10-1403 directly. The linear regression provides a more consistent means of evaluating aircraft when including future designs and commercial derivatives, and the difference between the linear regression and AFPAM 10-1403 data is small. The linear regression for load and unload ground times amounted to approximately 116 minutes of fixed ground time plus four minutes per pallet position.

AFPAM 10-1403 ground time estimates may not be achievable during long durations of peak operations. In particular, the AFPAM 10-1403 ground time estimates do not explicitly include delays due to

Figure 4.4
AFPAM 10-1403 Load and Unload Ground Times for C-130, C-17, and C-5



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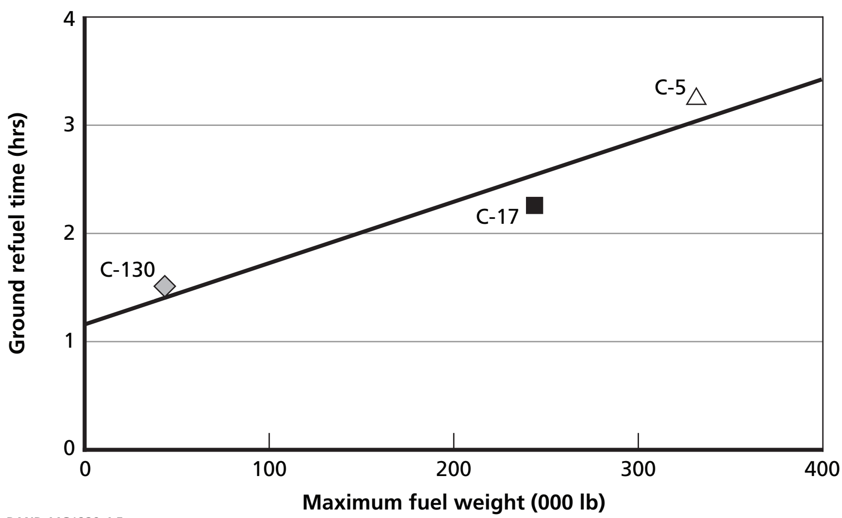
[13] These ground times were considered to be fixed for each alternative and not to be functions of the amount of cargo loaded or unloaded or the amount of fuel added. This is consistent with the formulation of AFPAM 10-1403.

weather, deicing, cargo availability, material handling equipment availability, and air traffic. Therefore, we used a ground efficiency factor of 85 percent to account for these factors. This increased the ground times to approximately 137 minutes of fixed ground time plus 4.6 minutes per pallet position.[14]

Aircraft refueling times were also based on AFPAM 10-1403 refueling times for the C-130, C-17A, and C-5. Again, a linear regression, as shown in Figure 4.5, determined the relationship between maximum fuel weight (MFW) and refuel time. This regression produced a refuel time of approximately 70 minutes of fixed ground time plus 21 seconds for every 1,000 pounds of fuel. As with the load and unload times, we applied an 85 percent efficiency factor to refueling stops.

In addition to ground times for load, unload, and refueling, additional ground time was necessary for maintenance work when the air-

Figure 4.5
AFPAM 10-1403 Refuel Times for C-130, C-17, and C-5



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14 Loading and unloading times (fixed and per pallet) were considered the same for all aircraft. Although the high deck and side door of some commercial aircraft may present difficulties, these aircraft also tend to carry only single pallets, which are easier to load.

craft was still in an MC state. Specifically, this amounted to 12 hours of ground time for every 100 hours of flight time to account for routine maintenance operations, such as basic preflight, tire changes, fluid top-offs, and off-station deferred maintenance items.

Aircraft Flight Times

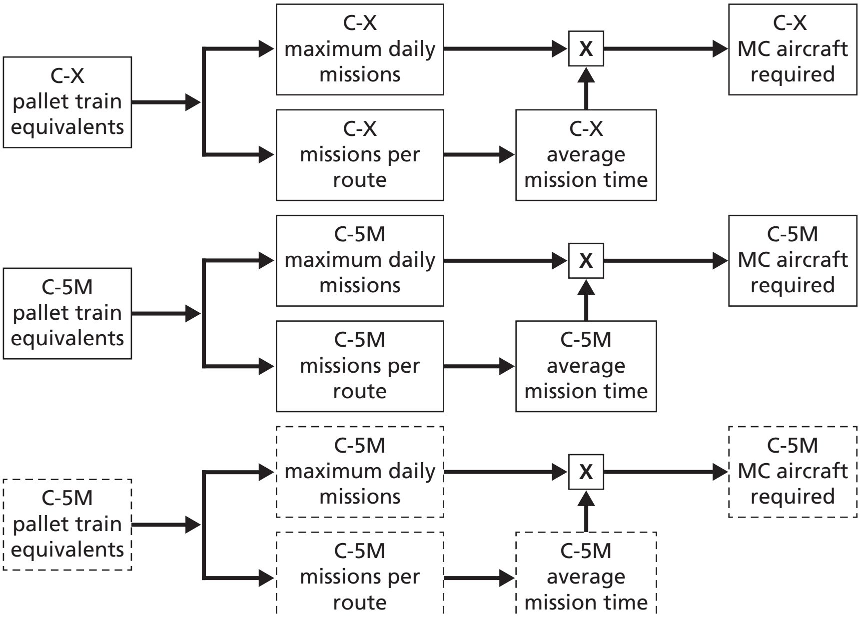
Flight times and fuel burn were broken up into several distinct phases. These included start engine, taxi, takeoff (STTO), climb, cruise, and approach and land. STTO time estimate for all aircraft alternatives was 20 minutes, and the approach and land time estimate for all aircraft alternatives was ten minutes. Time to climb data came from aircraft performance data, which expressed time to climb as a function of initial altitude, final altitude, and weight. The model simply performed a table lookup and interpolation for the time to climb. Optimum aircraft cruise performance was expressed as optimum altitude, optimum Mach number, and specific range at those altitudes and Mach numbers for three distinct weights. The three weights were approximately OEW, MGTOW, and halfway between OEW and MGTOW. By sampling the data at three points, we could fit a quadratic equation to the data to allow analytic integration. Appendix B presents additional details on the flight time calculations and justification for the use a quadratic fit.

Compute Fleet Size and Relative Aircraft Effectiveness

Knowing the number of missions per route allows calculation of the average mission time. Multiplying the maximum number of daily missions by the average mission time gives the number of MC aircraft required. We followed this process for three cases (see Figure 4.6): the C-X for the C-X compatible cargo, the C-5M for the C-X compatible cargo, and the C-5M for the C-X incompatible cargo (dashed-line boxes).

As discussed previously, dividing the number of MC aircraft gives the relative effectiveness of C-X to the C-5M for the cargo that the C-X can carry. For each C-X, the process described above is used to determine the C-5M fleet size required to transport cargo that the C-X

Figure 4.6
Number of Mission-Capable Aircraft Required



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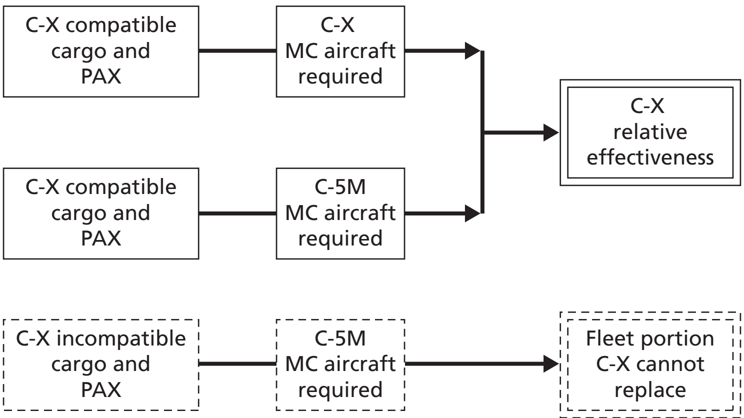
could not transport (see Figure 4.7). Appendix A offers examples of these calculations.

Effectiveness Results

This section presents the results of the effectiveness analysis for each aircraft alternative. The entire MCRS-16 log file was flown against the C-5M to express the total demand in terms of C-5M equivalent aircraft. The total demand was for 117 MC C-5M equivalent aircraft.

The effectiveness of each alternative was expressed in terms of two key parameters: the number of C-X aircraft required to carry the C-X compatible cargo (given limitations on the size of cargo an aircraft can carry) and the number of C-5M equivalent aircraft needed to carry the residual cargo (the C-X incompatible cargo). See Table 4.1.

Figure 4.7
C-X Relative Effectiveness and Fleet Portion



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For comparison, the table also shows the relative effectiveness of each alternative as the ratio of alternative aircraft to C-5M equivalents. For example, one MC BWB-100++ is as effective as 1.104 MC C-5Ms; thus, only 106 MC BWB-100++ aircraft are required to meet the demand for 117 MC C-5M equivalents. Finally, where appropriate, Table 4.1 gives the number of MC C-5M equivalents needed to carry the residual cargo a given alternative cannot carry because of the limitations on the size of cargo it can carry.

The table is broken up into two key sections: the six aircraft on the top are fully capable of carrying all the cargo. Thus, each can operate as a single fleet or can be part of a mixed fleet, and we have denoted them Category A aircraft. The seven aircraft on the bottom are not fully capable because of the cargo limitations discussed above.[15] These aircraft, which we call Category B, can operate only as part of a mixed fleet that includes some Category A aircraft. Note that SBW-75 appears twice, once in the top section, as SBW-75.1, and once in the bottom section, as SBW-75.2. As Table 4.1 shows, the relative effectiveness

[15] Since SBW-75.1 and SBW-75.2 are the same aircraft, with only the deck configurations differing, the SBW-75 is considered to be a Category A aircraft.

Table 4.1
Aircraft Alternative Effectiveness

	Alternative	MC C-X Aircraft Required to Carry Compatible Cargo	MC C-5M Equivalent Capability of C-X Aircraft	Relative Effectiveness	MC C-5M Equivalents for C-X Incompatible Cargo	Maximum Lift Capability from C-X (percent)
Category A	BWB-100++	106	117	1.104	0	100
	An-124	113	117	1.035	0	100
	C-5A/B	117	117	1.000	0	100
	C-5M / C-84X	117	117	1.000	0	100
	SBW-75.1	120	117	0.975	0	100
	C-17A / C-59X	259	117	0.452	0	100
Category B	C-17FE	244	108	0.443	9	92
	A400M	355	108	0.304	9	92
	Il-76	255	103	0.404	14	88
	BWB-100[a]	163	98	0.601	19	84
	C-747	110	89	0.809	28	76
	SBW-75.2[b]	68	74	1.088	43	63

Table 4.1—Continued

	Alternative	MC C-X Aircraft Required to Carry Compatible Cargo	MC C-5M Equivalent Capability of C-X Aircraft	Relative Effectiveness	MC C-5M Equivalents for C-X Incompatible Cargo	Maximum Lift Capability from C-X (percent)
B (cont.)	C-777	92	69	0.750	48	59
	C-767	99	53	0.535	64	45

[a] The BWB-100 is itself a Category B aircraft; however, it is only considered as part of a Category A program (BWB-100 + BWB-100++).

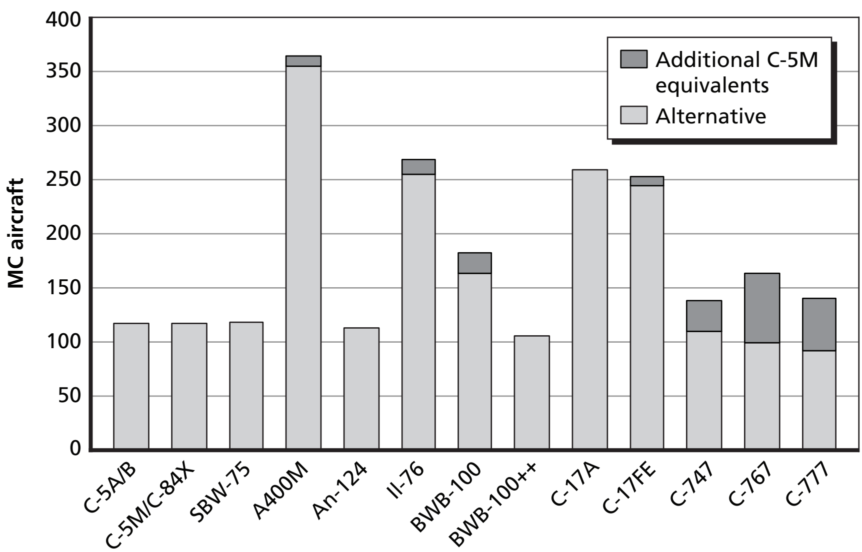
[b] The SBW-75.2 is a Category B configuration; however, the actual airframe (SBW-75) is a Category A aircraft.

of SBW-75.2, measured as the number of MC C-5M aircraft to MC SBW-75.2 aircraft required to carry the SBW-75.2 compatible cargo, is 1.088, but the relative effectiveness of SBW-75.1 is 0.975. Since the SBW-75.2 has a higher relative effectiveness, it is the preferred configuration. That means that a single fleet of SBW-75s should consist of the maximum number of double-deck configurations, and the remainder of the fleet should be single-deck configurations.

The results shown in Figure 4.8 repeat the data shown in Table 4.1 and show the number of each alternative required to recapitalize the entire fleet. Several of the options, the Category B aircraft, show additional C-5M equivalents that are necessary.

As discussed earlier, the C-X incompatible cargo is expressed in terms of MC C-5M equivalents required. All Category B aircraft have incompatible cargo, expressed as the number of MC C-5M equivalent aircraft required to carry that incompatible cargo. This requirement for

Figure 4.8
Mission-Capable Aircraft Required to Meet the Demand



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additional MC C-5M equivalents can be fulfilled by any Category A aircraft.[16]

An almost unlimited number of fleet combinations can meet the mission; however, this study limited alternative fleets to the C-5 and C-17A fleet followed by a Category A aircraft or to the C-5 and C-17A fleet followed by a mixed fleet of a Category B aircraft and a Category A aircraft. We looked at a wide set of alternative fleets. A few examples of these fleets with equal capability are shown in Table 4.2.

Table 4.2
Equivalent Fleet Examples

Fleet	Alternative	MC Aircraft	MC C-5M Equivalents
1	C-5A	13	13
	C-5M	33	33
	C-17A	157	71
2	C-84X	117	117
3	C-59X	259	117
4	C-747	110	89
	C-84X	28	28
5	C-747	110	89
	C-59X	62	28
6	SBW-75.1	45	44
	SBW-75.2	68	74
7	C-767	99	53
	SBW-75.1	19	21
	SBW-75.2	45	44
8	C-767	99	53
	BWB-100++	58	64

[16] For example, the C-747 has a requirement for 28 C-5M equivalents for carrying the C-747 incompatible cargo; these 28 C-5M equivalents could be either 28 C-84Xs (28 × 117 ÷ 117 = 28) or 62 C-59Xs (28 × 259 ÷ 117 = 62).

The first fleet example, Fleet 1, is essentially the current fleet after all C-5Bs are modified into C-5Ms. Fleets 2 and 3 represent complete recapitalizations with C-84X or C-59X, respectively. Fleets 4 and 5 are mixed fleets with a commercial derivative and the low-risk C-84X or C-59X, respectively. The C-747 fleet size is set to the maximum useful MC C-747 fleet size, 110; the remainder of the requirement is met by either the C-84X or C-59X. Fleet 6 is a pure fleet of SBW-75, where the fleet has been broken up into single-deck or double-deck configurations. Fleets 7 and 8 show mixed fleets of a C-767 with a more advanced technology aircraft. Note that all fleet examples shown in Table 4.2 have total MC C-5M equivalents equal to or greater than the requirement for 117.[17] Again, the fleets shown in Table 4.2 are purely examples and do not represent preferred solutions.

The fleet each year in the analysis was sized to meet but not exceed the requirement for 117 C-5M equivalents each year. Because of this, we did not consider fleets that significantly exceeded the requirement and did not examine the possibility of not retiring the additional 22 C-5As as planned, because retention of these aircraft would create excess capability.

Options Considered for Follow-On Fleet

As discussed previously, the aircraft alternatives can be broken up into two categories. We analyzed all Category A aircraft as a single fleet, as well as each Category B aircraft followed by a Category A aircraft.[18] The only exception is that some Category B aircraft can be followed by the BWB-100, itself a Category B aircraft, then by the BWB-100++. This is because much of the development cost is split between BWB-100 and BWB-100++; a mixed fleet that includes both the smaller BWB-100 and larger BWB-100++ may therefore make sense.

Although the BWB-100 is itself a Category B aircraft, the BWB-100 followed by BWB-100++ is being sold as a single risk-

[17] Some fleets slightly exceed the requirement for 117 because of integer rounding.

[18] The mixed-fleet options did not include the An-124.

mitigating program. Specifically, the BWB-100++ is an enlarged BWB-100 with many common parts. Therefore, throughout this analysis, BWB-100 followed by BWB-100++ is considered a single program.

The following pure Category A fleet options, as well as the BWB-100 and BWB-100++ combination, were considered:

- BWB-100 followed by BWB-100++
- BWB-100++
- SBW-75
- C-59X
- C-84X
- An-124[19]
- C-17A restart.

The mixed fleets of Category B and Category A aircraft are

- A400M followed by BWB-100++, SBW-75, C-59X, or C-84X
- C-17FE followed by BWB-100++, SBW-75, C-59X, or C-84X
- C-747 followed by BWB-100 and BWB-100++, BWB-100++, SBW-75, C-59X, or C-84X
- C-767 followed by BWB-100 and BWB-100++, BWB-100++, SBW-75, C-59X, or C-84X
- C-777 followed by BWB-100 and BWB-100++, BWB-100++, SBW-75, C-59X, or C-84X
- Il-76 followed by BWB-100 and BWB-100++, BWB-100++, SBW-75, C-59X, or C-84X.[20]

Note that the BWB-100 and BWB-100++ combination is not an option for the A400M and the C-17FE. This is because both the A400M and C-17FE have greater carrying capability than the BWB-100, meaning that, with a maximized number of A400M or C-17FE aircraft, no cargo is left for the BWB-100 to carry. We did not

[19] We handled An-124 cost-effectiveness parametrically because good cost estimates do not exist.

[20] We handled Il-76 cost-effectiveness parametrically because good cost estimates do not exist.

consider a C-17A restart along with a Category B aircraft because the time between when the C-17A line would be shut down and after all Category B aircraft have been procured would be too long for an effective restart. Table 4.3 summarizes the mixed-fleet options.

For the two low-rate C-17A production cases, we considered only a high-rate C-17A follow-on aircraft.

Table 4.4 presents a complete list of all aircraft alternatives in terms of TAI. This represents only fleets consisting exclusively of future aircraft and does not incorporate any of the C-5 and C-17A fleet.

Table 4.3
Mixed Fleets Considered

		Category A				
		BWB-100 + BWB-100++	BWB-100++	SBW-75	C-59X	C-84X
Category B	A400M		X	X	X	X
	C-17FE		X	X	X	X
	C-747	X	X	X	X	X
	C-767	X	X	X	X	X
	C-777	X	X	X	X	X
	Il-76		X	X	X	X

Table 4.4
All Future Fleet TAI Combinations

	Fleet Component	TAI	Fleet Component	TAI	Fleet Component	TAI
Category A	BWB-100	230	BWB-100++	24		
	BWB-100++	149				
	An-124	159				
	C-84X	165				
	SBW-75	158				
	C-17A /C-59X	364				
Category B	A400M	499	BWB-100++	12		
	A400M	499	C-84X	13		
	A400M	499	SBW-75	13		
	A400M	499	C-59X	28		
	C-17FE	343	BWB-100++	12		
	C-17FE	343	C-84X	13		
	C-17FE	343	SBW-75	13		
	C-17FE	343	C-59X	28		
	C-747	155	BWB-100	22	BWB-100++	24
	C-747	155	BWB-100++	36		
	C-747	155	C-84X	39		
	C-747	155	SBW-75	40		
	C-747	155	C-59X	87		
	C-767	140	BWB-100	106	BWB-100++	22
	C-767	140	BWB-100++	82		
	C-767	140	C-84X	90		
	C-767	140	SBW-75	88		
	C-767	140	C-59X	198		
	C-777	130	BWB-100	68	BWB-100++	23

Table 4.4—Continued

	Fleet Component	TAI	Fleet Component	TAI	Fleet Component	TAI
Category B (cont.)	C-777	130	BWB-100++	61		
	C-777	130	C-84X	67		
	C-777	130	SBW-75	68		
	C-777	130	C-59X	149		
	Il-76	359	BWB-100++	18		
	Il-76	359	C-84X	20		
	Il-76	359	SBW-75	20		
	Il-76	359	C-59X	43		

CHAPTER FIVE

Cost Analysis Methodology and Results

This chapter presents the cost analysis for all aircraft alternatives in this study. All costs are expressed in FY 2011 dollars. There are five cost categories: nonrecurring, procurement, military construction, operating and support (O&S), and disposal. We assumed that military construction and disposal do not differ significantly between alternatives and therefore do not consider them in the analysis. We further used an infinite time horizon to compute the NPVLCC for each alternative. Our calculations thus consisted of the following:

- **RDT&E and procurement costs.** The RDT&E and procurement costs for each alternative are based on cost-estimating relationships (CERs). We used historical aircraft program data to derive these CERs, which are a function of aircraft empty weight and material composition. Procurement CERs consisted of the cost to procure the first unit and a learning rate. The learning rate represents the decrease in unit cost from the first unit for every doubling of total aircraft produced. For example, a learning rate of 90 percent means that the second unit costs 90 percent of the first, and the fourth unit costs 81 percent of the first.
- **O&S costs, excluding crew and fuel.** We also derived CERs for O&S costs, excluding fuel and crew. The O&S cost estimate is a function of the average age of the fleet,[1] whether or not significant

[1] Questions remain about whether age-related O&S effects are appropriate for this kind of analysis. There is no general agreement now in the defense research community about the issue of age-related O&S cost growth. Due to the multicollinearity of aircraft calendar age

contractor support was being utilized, whether or not the aircraft was a tanker, the empty weight of the aircraft, the total annual FH, and the total inventory.

- **Fuel costs.** Fuel costs assume a price of $2.57 (FY 2011) per gallon.[2] We used the same flight profiles as for computing the effectiveness of each alternative in performing the MCRS-16 log file missions to calculate fuel burn per hour of flying.
- **Crew costs.** We estimated annual crew costs as $138,727 per officer and $71,812 per enlisted crew member.[3]

The real discount rate for this analysis was 2.70 percent, which is the 30-year real discount rate published in Office of Management and Budget Circular No. A-94 Revised December 2009.

Fleet Size

The chosen retirement schedule gives the shortfall, expressed in terms of C-5M equivalents, each year. We used the results of the effectiveness analysis to convert this shortfall into a quantity of MC aircraft for each alternative. Finally, dividing by the availability and allowing 2.5 percent of fleet to be devoted to training yielded TAI.[4] This TAI number is used for the calculation of both sustainment costs and procurement costs.

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and fiscal year, it is difficult to obtain statistically precise results on the comparative impact of each of the two on costs. In keeping with the practice of the Aerial Refueling Analysis of Alternatives, aircraft age was included in the approach here. Admittedly, in our current state of knowledge, this is a judgment call, but one made in consultation with knowledgeable persons in the air mobility analytic community.

[2] The $2.57 (FY 2011) was based on the KC-X Tanker Modernization Program Request for Proposals value of $2.54 (FY 2010) (Solicitation FA8625-10-R-6600-SpecialNotice). This request for proposals was later, after the start of this project, updated and amended to $3.03 (FY 2011).

[3] Air Force Instruction 65-503, *Military Annual Standard Composite Pay Rates*, December 6, 2010.

[4] MCRS-16 notes that although 5 percent of the TAI is devoted to training, up to 50 percent of these can be diverted, leaving only 2.5 percent fully devoted to the training mission.

RDT&E and Procurement Costs

RDT&E costs for commercial derivatives, as well as for existing military airlifters, were assumed to be zero. While modifying a commercial aircraft into a military aircraft would indeed entail RDT&E costs, we used list prices for all commercial aircraft. Use of list prices provides a sufficiently large cost buffer to cover any necessary modifications.

We used CERs to estimate RDT&E and procurement costs for the other alternatives. These CERs were derived from historical aircraft program data and are a function of aircraft empty weight and material composition. We assumed that engines and avionics would all be available from other applications (off the shelf); hence, no development cost would be required. Engine production costs were estimated using a CER based on maximum thrust. We assumed the avionics suites would be the same for all aircraft because they all have the same mission and based the avionics production costs on the C-17A suite. The specific methods are an update of those used in the Analysis of Alternatives for KC-135 Recapitalization.[5]

The lowest RDT&E cost, at $1.4 billion, was a C-17A restart, which assumes that much of the C-17A tooling has been preserved.[6] The second-lowest RDT&E cost, at $6.5 billion, was a C-17FE. The C-17FE is essentially a narrow-body C-17A with enhancements to improve soft-field access. Because the C-17FE has significant commonality with the C-17A, the RDT&E cost is lower than it would be for a new program. See Figure 5.1.

Table 5.1 repeats the RDT&E data shown in Figure 5.1 and gives the cost to procure the first unit (T1 procurement) and learning rate. A learning rate of 100 percent means that there is no learning and that the cost of each unit remains unchanged. All existing aircraft and commercial-derivative aircraft have a learning rate of 100 percent. All

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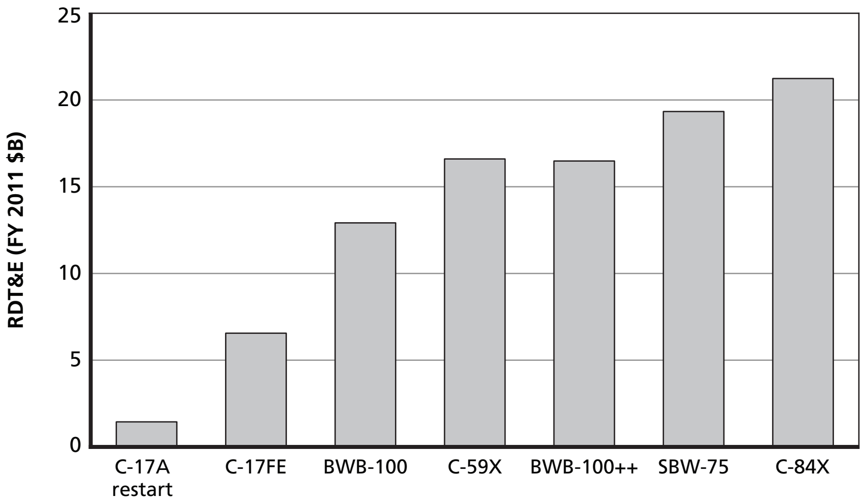
[5] Fred Timson, *Analysis of Alternatives (AoA) for KC-135 Recapitalization, Appendix E: Acquisition Costs for New-Design Alternatives*, Santa Monica, Calif.: RAND Corporation, MG-460-AF, 2005, Not available to the general public.

[6] John C. Graser, Edward G. Keating, Guy Weichenberg, Michael Boito, Soumen Saha, Robert G. DeFeo, and Steven Strain, *Options for and Costs of Retaining C-17 Aircraft Production-Only Tooling*, Santa Monica, Calif.: RAND Corporation, TR-1143-AF, 2012.

Figure 5.1
RDT&E Costs for Alternative Aircraft



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new aircraft were assumed to have a learning rate of 90 percent. Based on Selected Acquisition Report (SAR) data, historical learning rates for the C-5B, C-17A, and C-130J were estimated at 80, 90, and 100 percent, respectively. The 90 percent thus represents a median value.[7] Only the C-17A restart is different, because of retained knowledge and stored tooling, with a slower learning rate estimated at 92.6 percent.[8] This estimate was based on consultations with RAND colleagues regarding the amount of retained knowledge and stored tooling.[9]

We considered several scenarios for C-17A production, each with different production rates, which affects unit cost. To determine the

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[7] A description of the SAR data analysis can be found in Joseph G. Bolten, Robert S. Leonard, Mark V. Arena, Obaid Younossi, and Jerry M. Sollinger, *Sources of Weapon System Cost Growth: Analysis of 35 Major Defense Acquisition Programs*, Santa Monica, Calif.: RAND Corporation, MG-670-AF, 2008.

[8] When calculating the unit cost for a C-17A restart aircraft, the unit counting is reset, meaning the first unit produced after the restart is considered unit 1. Thus, the unit number is the number of post-restart C-17A, not the total number of C-17As ever produced.

[9] These were the authors of Graser et al., 2012.

Table 5.1
Alternative Costs and Learning Rates

Alternative	RDT&E ($M)	T1 Procurement ($M)	Learning Rate (percent)
C-5A RERP		113.9	100.0
C-5B RERP		113.9	100.0
C-767		191.7	100.0
A400M		210.4	100.0
C-17A (15/yr)		294.3	100.0
C-777		306.3	100.0
C-17A (6/yr)		355.0	100.0
C-747		361.9	100.0
C-17A (2/yr)		444.4	100.0
C-17A restart	1,401	472.5	92.6
C-17FE	6,500	571.9	90.0
BWB-100	12,848	582.5	90.0
C-59X	16,546	658.5	90.0
BWB-100++	16,444	760.1	90.0
SBW-75	19,315	797.6	90.0
C-84X	21,220	845.6	90.0

rates to use, we used a rate slope of 86.8 percent, based on historical data and consultations with RAND colleagues.[10] As with a learning rate slope, this means that, if two units are produced in a given year, the unit cost for each unit is 86.8 percent of what it would have been had only one unit been produced. Similarly, if four units are produced in a given year, the unit cost for each unit is 75.3 percent of what it would have been had only one unit been produced. Starting from the estimated cost of producing one unit per year, $512.2 million,

[10] These were the authors of Graser et al., 2012.

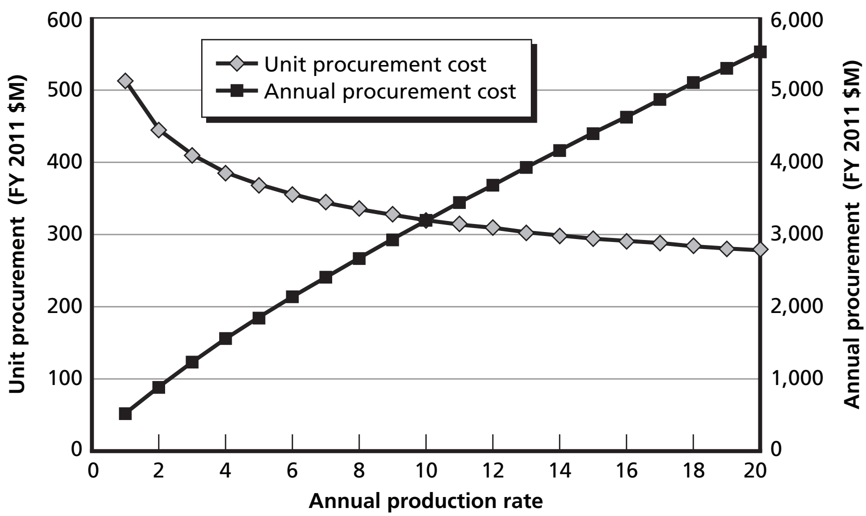
Figure 5.2 shows the decrease in unit procurement cost as a function of production rate.

For some aircraft, such as the An-124 and the Il-76, good cost estimates do not exist. We assessed these parametrically, determining the cost at which each would be cost-effective. If the aircraft cost less than this threshold, it would be cost-effective; otherwise, it would not be.

Operating and Support Costs

The O&S costs fell into three categories: O&S costs excluding fuel and crew, fuel, and crew. The data for O&S costs excluding fuel and crew came from assessment of historical data using CERs. Fuel costs were based on average fuel burn, in terms of gallons per hour, given the actual flying pattern of the aircraft in the effectiveness model. Finally, crew costs were based on the crew ratio and crew costs.

Figure 5.2
C-17A Procurement Cost Dependency on Production Rate



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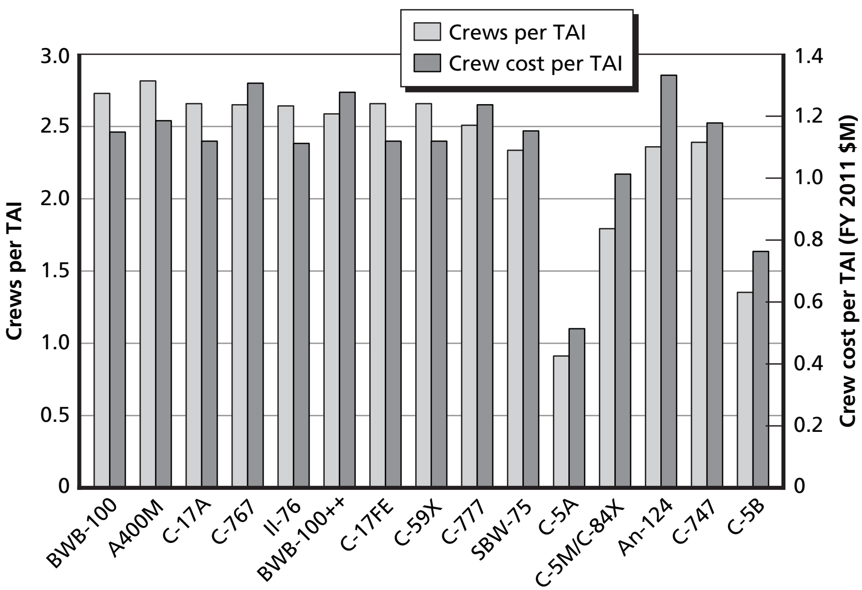
Crew Costs

The effectiveness analysis produced the average number of FH per day, which determined the total flying over a 30-day period. Dividing this 30-day FH number by the 30-day crew limit of 125 FH produced the crew ratio for each alternative per MC aircraft.[11] Multiplying this crew ratio by the aircraft availability produced the crew ratio per TAI. Figure 5.3 shows both the crew ratio and the crew cost per TAI. The A400M has the highest crew ratio of any aircraft because it is slower and therefore has longer flight times. The C-5A has the lowest crew ratio because of its very low availability.

Figure 5.3
Crew Costs for Alternative Aircraft



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11 Air Force Instruction 11-202, Vol. 3, *Flying Operations: General Flight Rules*, October 22, 2010.

O&S Costs Excluding Fuel and Crew

We also derived CERs for O&S costs, excluding fuel and crew, in this case using historical data for FYs 1996 through 2009 for the C-5A, C-5B, C-130E, C-130H, C-130J, C-141B, C-141C, KC-135E, KC-135R, KC-135T, KC-10A, and C-17A. In particular, the logarithm of O&S costs is expressed as a linear function which included a constant term, the average age of the fleet, whether or not significant contractor support was being utilized, whether or not the aircraft was a tanker, the logarithm of the empty weight of the aircraft, the logarithm of the total annual FH, and the logarithm of the total inventory. Specifically, the chosen model was of the form

$$\begin{aligned}\ln(O\,\&\,S) = \alpha_0 + \alpha_1\overline{Age} + \alpha_2\delta_{CLS} + \alpha_3\delta_{Tanker} \\ + \alpha_4\ln(EW) + \alpha_5\ln(FH) + \alpha_6\ln(TAI)\ ,\end{aligned}$$

where

$\alpha =$ the regression coefficient

$\overline{Age} =$ the average age of the fleet

$\delta_{CLS} =$ is 1 if the aircraft relies heavily on contractor logistic support and 0 otherwise

$\delta_{Tanker} =$ is 1 if the aircraft is a tanker and 0 otherwise

$EW =$ the empty weight of the aircraft

$FH =$ the flying hours of the aircraft

$TAI =$ the total aircraft inventory

$O\,\&\,S =$ the annual O&S cost.

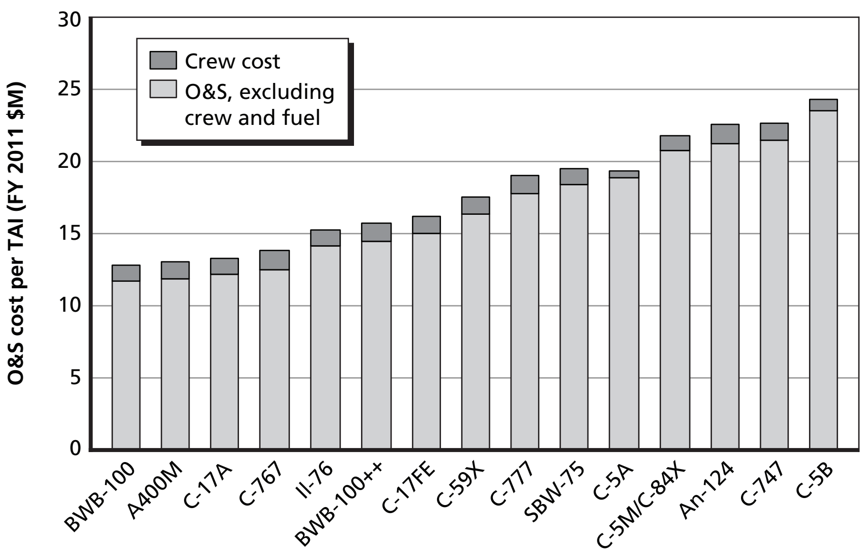
The regression produced very good results (Table 5.2), with all the coefficients statistically different from zero and an R^2 of 0.963. Note that, although the R^2 value is quite high, the standard error on the log of O&S cost is 0.182, which translates to an error of about ±20 percent on O&S cost.

Figure 5.4 shows the O&S costs, excluding fuel, for all the aircraft we analyzed, along with intervals corresponding to one standard error. This figure assumes that each aircraft is part of a fleet of 100 air-

Table 5.2
O&S Regression Model Statistics

Variable	Model	Standard Error	T-Statistic
Constant	3.916	0.415	9.445
Average Age	0.006	0.002	3.700
CLS	–0.204	0.063	–3.227
Tanker	–0.223	0.042	–5.341
Empty Weight	0.675	0.030	22.331
Annual Flight Hours	0.611	0.045	13.495
TAI	0.394	0.050	7.961
R^2	0.963		
Standard Error	0.182		
Degrees of Freedom	144		

Figure 5.4
O&S Costs, Excluding Fuel, for Alternative Aircraft



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craft; flies 1,000 hours per year; is zero years of age; and, other than the C-17A, does not have significant contractor logistics.

Fuel Costs

One of the outputs of the effectiveness model was the average fuel burn of each aircraft, which was based on the flying profile of the aircraft. Using the expected peacetime annual flight hours, we converted this to an annual fuel burn. The estimated cost of fuel was $2.57 (FY 2011). We examined the effects of higher fuel costs in more detail through a sensitivity analysis and found that higher fuel costs in general strengthen the conclusion that the most cost-effective options are the BWB-100++ or a commercial derivative aircraft. Appendix C presents further details on the fuel burn rate and annual fuel cost of the alternatives.[12]

Net Present Value Life-Cycle Cost Methodology

Chapter Six presents results in terms of NPVLCCs, which assume an infinite time horizon. This method avoids the problem of favoring a particular alternative simply because its timing produces a lower net present value cost given an artificially chosen time horizon. To compute NPVLCC based on an infinite time horizon, we added the total NPVLCC for the C-5 and C-17A fleet through complete retirement to the NPVLCC for a follow-on fleet, assuming the follow-on fleet procurement and RDT&E recurred every 30 years. The resulting total NPVLCC thus represents the amount of money today that would fund the C-5 and C-17A fleet through retirement, the follow-on fleet, and subsequent follow-on fleets every 30 years indefinitely. The individual NPVLCCs for the follow-on fleet and all subsequent follow-on fleets can be computed by calculating the NPVLCC for the first-generation follow-on fleet and multiplying this by an appropriate infinite sum based on the time between generations, which we assumed to be 30 years.

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[12] Appendix C is in Mouton et al., forthcoming.

Calculating NPVLCC requires modeling the time expenditure for RDT&E and procurement spending. For example, if an equal amount of money was spent on RDT&E in year one and in year two, the net present value would be higher than if all the money was spent in just year 2. In addition to affecting the NPVLCC calculation, the spending profiles are critical to the analysis of annual expenditures. For example, the fact that RDT&E programs tend to be spread over a long period smooths out what would otherwise be dramatically large peaks in spending.

RDT&E and Procurement Spending Profiles

In general, both RDT&E and procurement costs are appropriated and spent over several years. The spending profiles we used are based on the work done for the Analysis of Alternatives for KC-135 Recapitalization.[13] In particular, RDT&E money for a new-design aircraft is appropriated over ten years, with the first appropriation seven years before first delivery; for a derivative-design aircraft, RDT&E money is appropriated over three years, with the first appropriation three years before first delivery. Similarly, procurement is appropriated over six years, with the first appropriation two years before delivery. Figure 5.5 shows these appropriations as percentages of total appropriations.

The RDT&E appropriations themselves are then spent over five years, with the first expenditure occurring in the year it is appropriated. Procurement money is spent completely in the year in which it is appropriated.

The total annual RDT&E is found by taking the convolution of the RDT&E appropriations with the annual spending of a single appropriation. Applying the annual spending shown in Figure 5.6 to each of the appropriations shown in Figure 5.5 produces the total annual spending for RDT&E. Figure 5.6 shows the total RDT&E spending given first delivery in year 1, as well as the total spending for each aircraft delivery in year 1.

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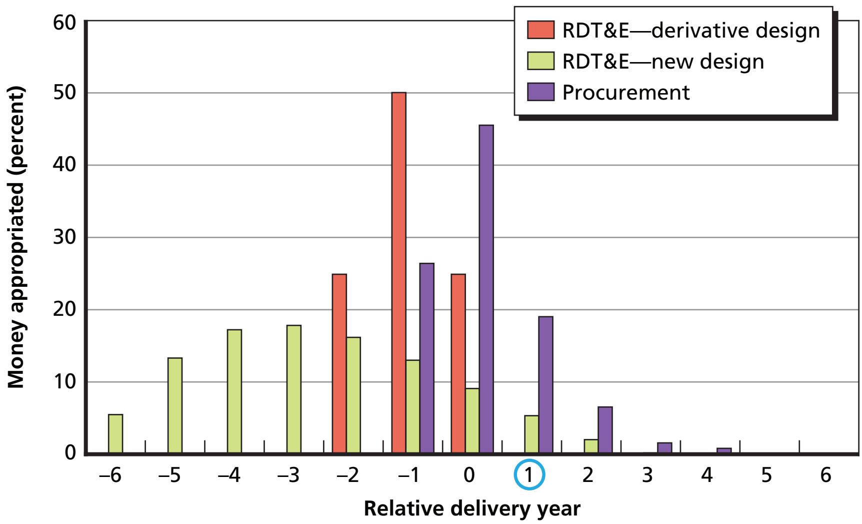
[13] Kennedy et al., 2005; Kennedy et al., 2006.

Figure 5.5
Annual Appropriations for RDT&E and Procurement with First Delivery and Delivery in Year 1, Respectively



SOURCES: Kennedy et al., 2005; Kennedy et al., 2006.
RAND *MG1238-5.5*

Summary Cost Data

The NPV cost of the strategic fleet has two elements. The first is the NPV associated with maintaining the current fleet, and the second is the NPV associated with replacing that fleet indefinitely into the future.

NPV of the C-5 and C-17A Fleet

The NPV of the C-5 and C-17A fleet is made up of the O&S costs for the C-5A, C-5M, and C-17A and the costs associated with RERPing the remaining C-5B and C-5C aircraft. See Figure 5.7.

NPV of Future Fleet Options

Figure 5.8 shoes the NPV of Category A aircraft, excluding fuel, for the baseline case. The figure shows that NPV costs for the BWB-100++ are significantly lower than for the others and that the highest NPV

Figure 5.6
Annual Spending for RDT&E and Procurement with First Delivery and Delivery in Year 1, Respectively

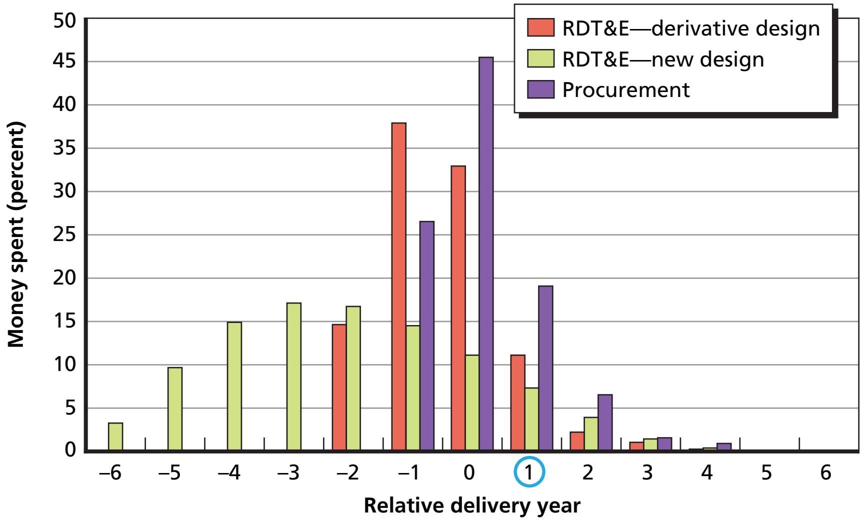


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Figure 5.7
Net Present Value Costs Associated with the Fleet of C-5s and C-17As

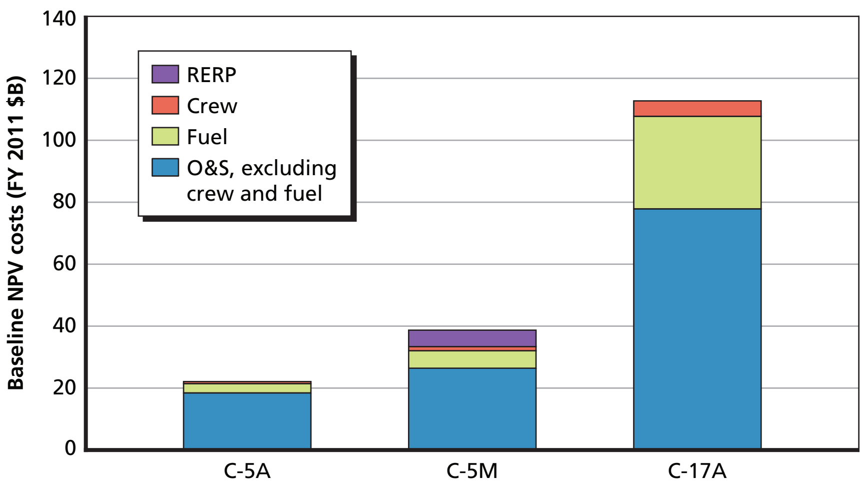

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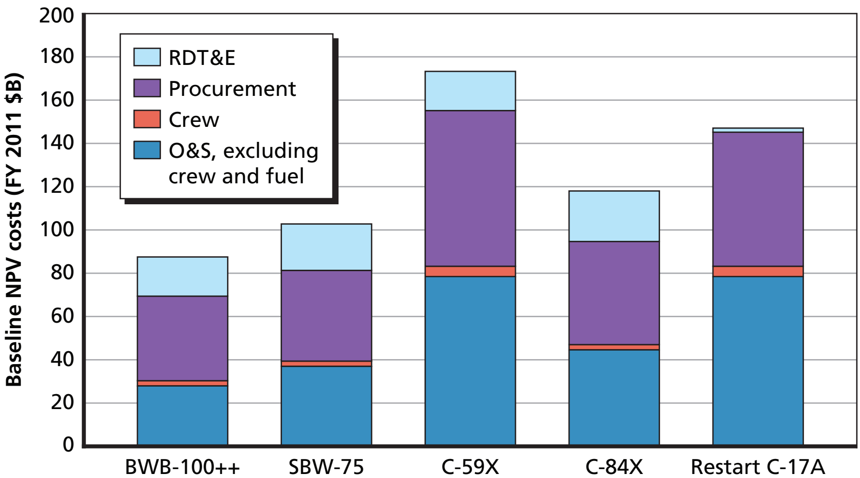
Figure 5.8
Net Present Value Costs Associated with the Category A Aircraft for the Baseline



RAND *MG1238-5.8*

costs are for the C-59X, which is due to the large required fleet size. The Restart C-17A case shows costs identical to those for the C-59X, except that the procurement and RDT&E costs for the former are lower because of retained knowledge.

CHAPTER SIX

Cost-Effectiveness Analysis

This chapter presents the results of the cost-effectiveness analysis. We considered ten potential courses of action that USAF could take for the C-5 and C-17A fleet. These options include various retirement profiles for the C-5 fleet and various levels of continued C-17A production. There were 34 steady-state future fleet options, including all the alternatives presented in Chapter Three.

The chapter is broken up into four main sections:

- **Baseline NPVLCC cost-effectiveness.** This section presents the NPVLCC cost-effectiveness of all cases we considered, covering all combinations of fleet options and retirement options. This includes analysis of C-17A continuation options.
- **Sensitivity analyses.** This section provides detailed sensitivity analyses of the results. These focus on some important assumptions, including BWB-100++ cost, C-5 and C-17A service lives, C-5A RERP cost, C-767 procurement cost, and continued C-17A production cost. Additional sensitivity analyses cover a reduced requirement level, fuel prices, and service life of future aircraft. All these sensitivity analyses show that the results presented in this document are robust.
- **Parametric analyses.** This section presents parametric analyses for the An-124 and Il-76, for which no reliable cost data were available; C-17A SLEP cost, since as of 2012 no good estimates exist for a SLEP program; and C-17A production continuation costs.

- **Annual expenditures analysis.** This section presents annual expenditures for various options. This is an important analysis because some options may offer a slightly higher NPVLCC but provide smoother annual expenditures, which can be very important in the budgeting process.

Baseline NPVLCC Cost-Effectiveness

We costed each follow-on and current C-5 and C-17A fleet option, forming a matrix of costs for each. The baseline case was considered to be the baseline C-5 and C-17A fleet option (retain 41 C-5As, RERP all C-5Bs and C-5Cs, and stop C-17A production at 221) and the C-84X (a new design C-5M aircraft). This option had a NPVLCC of $306.2 billion (FY 2011), and we measured all other options against this cost. Options with a NPVLCC less than $306.2 billion (FY 2011) are said to have *cost savings*, otherwise they are said to have *additional cost*.

Table 6.1 shows the cost-effectiveness relative to the baseline for each Category A alternative. Positive numbers represent cost savings; negative numbers (red cells) represent additional costs. In addition, the options within $1 billion of the most cost-effective solution for each row and for each column are shown in green, and their intersection is shown in dark green. It is very important to note that the choice of the best fleet alternative is nearly independent of the choice for the C-5 and C-17A fleet and vice versa.[1] Specifically, the table shows that the Baseline, Partially RERP C-5A, and Retire C-5A Starting in 2060 are robust regardless of alternative. Similarly, the BWB-100++ is robust regardless of the C-5 and C-17A option chosen. The BWB-100 followed by the BWB-100++ always has lower cost savings than the BWB-100++ alone, regardless of current fleet options. Therefore, the BWB-100 followed by the BWB-100++ is considered cost-inferior.[2] The C-59X and restart C-17A are considered to not be cost-effective

[1] This further supports the assertion that changes in fleet requirements and fleet retirements do not change the best alternatives for the future fleet.

[2] *Cost-inferior* means that there is always an option that provides greater cost savings.

Table 6.1
Cost Savings of Category A Fleet Alternatives

	C-5 and C-17A Fleet Option							
Fleet Alternative	**Baseline**	**Continue C-17A Production**	**Partially RERP C-5A**	**Retire C-5A in the Near Term**	**Limited C-5B RERP**	**Retire C-5A Starting in 2030**	**Retire All C-5 Starting in 2030**	**Retire C-5A Starting in 2060**
BWB-100 + BWB-100++	8.6	0.2	9.7	N/A	4.4	7.1	0.3	9.9
BWB-100++	37.6	28.9	39.3	N/A	33.7	38.5	36.3	39.0
SBW-75	16.4	7.6	16.9	N/A	12.6	14.7	10.1	16.8
C-59X	–63.6	–72.7	–67.3	N/A	–67.1	–75.3	–91.9	–66.0
C-84X	0.0	–8.8	–0.1	N/A	–3.9	–3.5	–10.2	0.1
Restart C-17A	–37.1	–46.0	–40.5	N/A	–40.7	–46.0	–61.2	–39.2

NOTES: Amounts in FY 2011 $B. Red cells indicate additional costs over the baseline; green cells are within $1 billion of the best for the row or column; dark green cells are within $1 billion of the best for the row and the column. All Category A fleet options with retiring the C-5A in the near term are marked N/A, because the new-design aircraft will not be ready for delivery in time and because the C-17A line cannot be restarted if it has not yet shut down.

because they always have additional cost beyond the baseline, regardless of current-fleet choices. Therefore, only the BWB-100++, SBW-75, and C-84X are carried forward as Category A options.

Table 6.2 shows the cost-effectiveness for mixed-fleet alternatives. Again, excluding one case, the most cost-effective future fleet is independent of the C-5 and C-17A option. The A400M and C-17FE are never cost-effective, regardless of the follow-on Category A aircraft or the C-5 and C-17A option. As with Category A aircraft, fleet alternatives that include both the BWB-100 and BWB-100++ are always cost-inferior to fleet alternatives with just the BWB-100++. Similarly, fleet alternatives with the C-59X are never cost-effective. In addition, fleet alternatives with the C-747 or C-777 are always cost-inferior to the C-767.

The only mixed-fleet alternatives carried forward are the C-767 followed by BWB-100++, SBW-75, or C-84X. Together with the Category A aircraft, we carried forward a total of six fleet alternatives. For clarity, Table 6.3 repeats these six options. It is always more cost-effective to purchase the BWB-100++ as a single fleet; however, it is always more cost-effective to purchase both the SBW-75 and C-84X as part of a mixed fleet with a C-767. This is because the BWB-100++ represents a dramatic technology improvement that more than offsets the costs associated with an early R&D program. On the other hand, it is better to delay the RDT&E associated with the modest technology SBW-75 and the current-technology C-84X.

In all cases, procuring the C-767 first reduces technology risk by allowing more development time and creates a hedge against technology changes. Therefore, even though the BWB-100++ preceded by the C-767 is cost-inferior to the BWB-100++, it does reduce technology risk and is therefore still considered a viable option.

Table 6.3 also shows the cost-effectiveness of the various options for the C-5 and C-17A fleet. Compared to the Baseline, Continue C-17A Production, Limited C-5B RERP, and Retire All C-5s Starting in 2030 are always cost-inferior. The Baseline, Retire C-5A in the Near Term, and Retire C-5A starting in 2030 are both cost-inferior to Retire C-5A Starting in 2060. Considering other aging aircraft, such

Table 6.2
Cost Savings of Mixed-Fleet Alternatives

Fleet Alternative	Baseline	Continue C-17A Production	Partially RERP C-5A	Retire C-5A in the Near Term	Limited C-5B RERP	Retire C-5A Starting in 2030	Retire All C-5s Starting in 2030	Retire C-5A Starting in 2060
A400M + BWB-100++	–144.7	–156.9	–153.8	–185.4	–146.5	–168.9	–203.3	–150.7
A400M + SBW-75	–146.1	–159.2	–157.1	–188.8	–147.9	–172.3	–206.9	–153.7
A400M + C-59X	–147.6	–161.7	–161.1	–192.9	–149.4	–176.3	–211.1	–157.4
A400M + C-84X	–146.9	–160.5	–158.7	–190.5	–148.6	–174.0	–208.7	–155.2
C-17FE + BWB-100++	–39.2	–50.2	–44.9	N/A	–42.8	–50.9	–65.4	–43.4
C-17FE + SBW-75	–40.6	–52.6	–48.2	N/A	–44.1	–54.3	–69.0	–46.5
C-17FE + C-59X	–42.1	–55.0	–52.2	N/A	–45.7	–58.4	–73.3	–50.1
C-17FE + C-84X	–41.3	–53.8	–49.9	N/A	–44.9	–56.0	–70.8	–48.0
C-747 + BWB-100 + BWB-100++	2.8	–4.9	4.1	–0.4	–1.5	1.9	–7.4	4.4
C-747 + BWB-100++	8.1	0.2	9.2	4.9	3.8	7.2	–1.7	9.3
C-747 + SBW-75	2.5	–6.1	2.0	–2.3	–1.6	–0.1	–9.5	2.6
C-747 + C-59X	–8.3	–18.8	–13.2	–17.8	–11.3	–15.5	–26.2	–11.9
C-747 + C-84X	0.3	–8.4	–0.5	–4.9	–3.7	–2.7	–12.3	0.1

Table 6.2—Continued

Fleet Alternative	Baseline	Continue C-17A Production	Partially RERP C-5A	Retire C-5A in the Near Term	Limited C-5B RERP	Retire C-5A Starting in 2030	Retire All C-5s Starting in 2030	Retire C-5A Starting in 2060
C-767 + BWB-100 + BWB-100++	15.2	7.1	16.3	14.3	11.1	15.3	5.3	16.6
C-767 + BWB-100++	29.1	20.7	30.4	28.5	25.0	29.6	21.1	30.3
C-767 + SBW-75	19.8	11.2	20.1	18.0	15.8	19.0	8.6	20.3
C-767 + C-59X	–16.5	–26.6	–20.9	–23.6	–19.6	–22.6	–39.2	–19.4
C-767 + C-84X	11.5	2.7	11.1	8.8	7.7	9.8	–2.4	11.5
C-777 + BWB-100 + BWB-100++	12.6	4.6	14.1	11.3	8.5	12.8	3.9	14.1
C-777 + BWB-100++	22.8	14.6	24.3	21.7	18.6	23.1	15.2	24.1
C-777 + SBW-75	16.4	7.8	16.8	14.2	12.4	15.7	6.7	16.9
C-777 + C-59X	–9.9	–20.2	–14.0	–17.2	–12.9	–15.8	–28.5	–13.0
C-777 + C-84X	9.6	0.8	9.4	6.5	5.7	8.0	–2.1	9.6

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs over the baseline; green cells are within $1 billion of the best for the row or column; dark green cells are within $1 billion of the best for the row and the column.

Table 6.3
Cost Savings of Six Fleet Alternatives

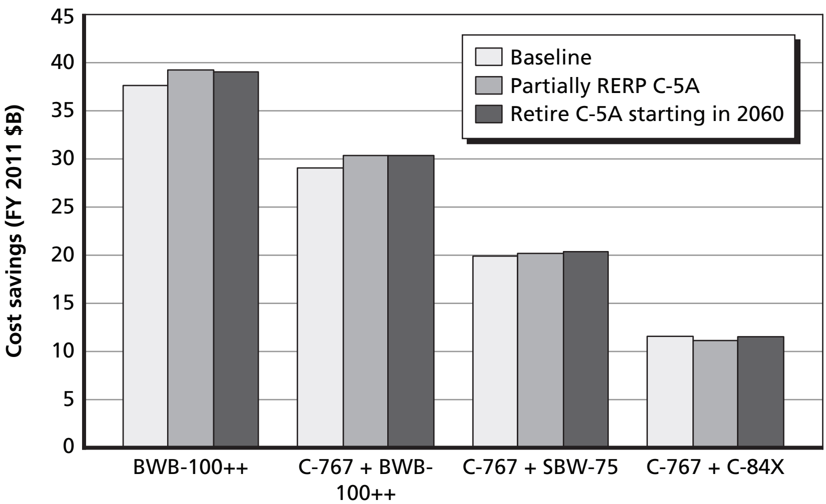
Fleet Alternative	Baseline	Continue C-17A Production	Partially RERP C-5A	Retire C-5A in the Near Term	Limited C-5B RERP	Retire C-5A Starting in 2030	Retire All C-5s Starting in 2030	Retire C-5A Starting in 2060
BWB-100++	37.6	28.9	39.3	N/A	33.7	38.5	36.3	39.0
SBW-75	16.4	7.6	16.9	N/A	12.6	14.7	10.1	16.8
C-84X	0.0	–8.8	–0.1	N/A	–3.9	–3.5	–10.2	0.1
C-767 + BWB-100++	29.1	20.7	30.4	28.5	25.0	29.6	21.1	30.3
C-767 + SBW-75	19.8	11.2	20.1	18.0	15.8	19.0	8.6	20.3
C-767 + C-84X	11.5	2.7	11.1	8.8	7.7	9.8	–2.4	11.5

NOTES: Amounts in FY 2011 $B. Red cells indicate additional costs over the baseline; green cells are within $1 billion of the best for the row or column; dark green cells are within $1 billion of the best for the row and the column.

as the B-52 and KC-135, it is plausible that the C-5A could continue to fly until 2060.

Figure 6.1 shows the results for the most cost-effective aircraft alternatives and C-5 and C-17A options. The SBW-75 alone is not included in this figure because the SBW-75 is always more cost-effective if it is first preceded by the C-767. The cost savings are highly dependent on the choice of fleet alternative and are rather insensitive to whether that choice is the baseline, a partial RERP of the C-5As, or the C-5As retire starting in 2060. The greatest savings come from the BWB-100++ fleet alternative; however, this option has a significant amount of technological risk. Therefore, if this technology is not ready for first delivery around 2033 or if the technology is significantly more costly than anticipated, the C-767 should be purchased. The C-767 should then be followed by the best aircraft alternative available for subsequent delivery. It is possible that the BWB-100++ would be available for first delivery around 2053; again, if it is not, either the SBW-75 or C-84X would still provide significant cost savings.

Figure 6.1
Cost Savings for Most Cost-Effective Options



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In all four cases, the options for the C-5A have a relatively small influence. In addition, other than the BWB-100++ case, all the best options include the initial procurement of the C-767. Again, this suggests that, unless a BWB-100++ appears technologically feasible at the time of procurement, a commercial derivative, such as the C-767, is a very cost-effective option.

Cost-Effectiveness of C-17A Production Continuation

We considered three different C-17A production continuation options. Two of these, low-rate production at six per year and low-rate production at two per year, are distinct because they must be followed by high-rate C-17A production. Specifically, the reason for keeping the C-17A line open at relatively high cost is that this may avoid future RDT&E expenses associated with a new production aircraft. This section therefore looks at these two low-rate options only in the context of the line being started up again at a high rate.

Continued C-17A Procurement at Six Aircraft per Year

This option continues procurement of six aircraft per year. Given this low rate of production and given that the higher unit cost might mean that Boeing cannot sell any additional aircraft to foreign manufacturers, the unit procurement cost would be $355 million (FY 2011). In this option, 114 additional C-17A aircraft are procured to first replace all the C-5As, followed by all the C-5Bs, followed by 14 C-5Ms. Since some of the C-5Ms are being replaced by the C-17As, no additional C-5Bs are RERPed in this case because it would not make sense to do so only to retire them in the near term. While the unit procurement cost is relatively high, this solution would allow C-17A production to later ramp up, thereby avoiding RDT&E costs. Because of this, we considered this solution only in the context of a transition from low-rate production of six per year to full production once older C-17A aircraft and C-5M aircraft begin to retire. The NPVLCC for this option was $45.2 billion (FY 2011) higher than that for the baseline C-84X. Compared to the option of low-rate C-17A production at six

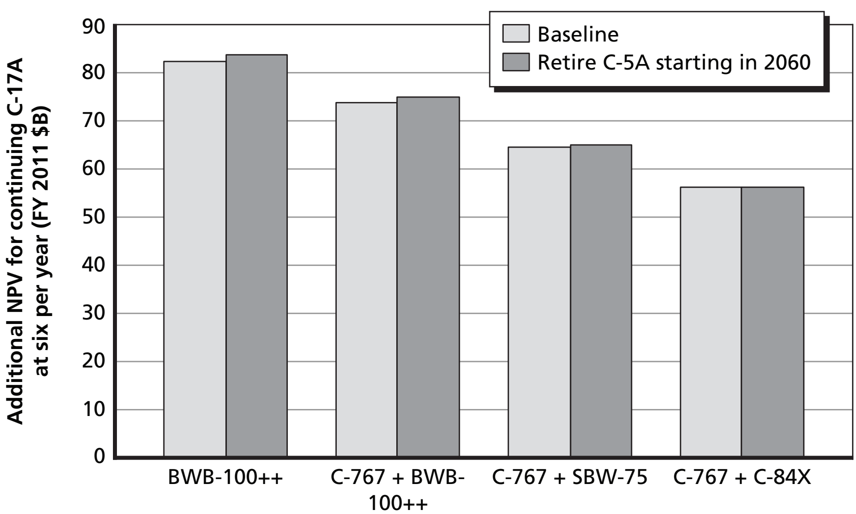
per year followed by high-rate C-17A production to the four most cost-effective options, continued C-17A production has significant additional NPVLCC. As Figure 6.2 shows, the additional NPVLCC associated with continued C-17A production is higher for the more cost-effective solutions, such as the BWB-100++.

Again, the results are relatively insensitive to the C-5A option. However, in all cases, the additional NPVLCC associated with continued C-17A production is very significant, indicating that in none of the scenarios considered was continued C-17A production even slightly cost-effective.

Continued C-17A Procurement at Two Aircraft per Year

This option continues procurement of two aircraft per year. Given this low rate of production and given that the higher unit cost might mean that Boeing cannot sell any additional aircraft to foreign manufactur-

Figure 6.2
Additional NPVLCC for Six-per-Year C-17A Continuation Compared to the Most Cost-Effective Aircraft Alternatives



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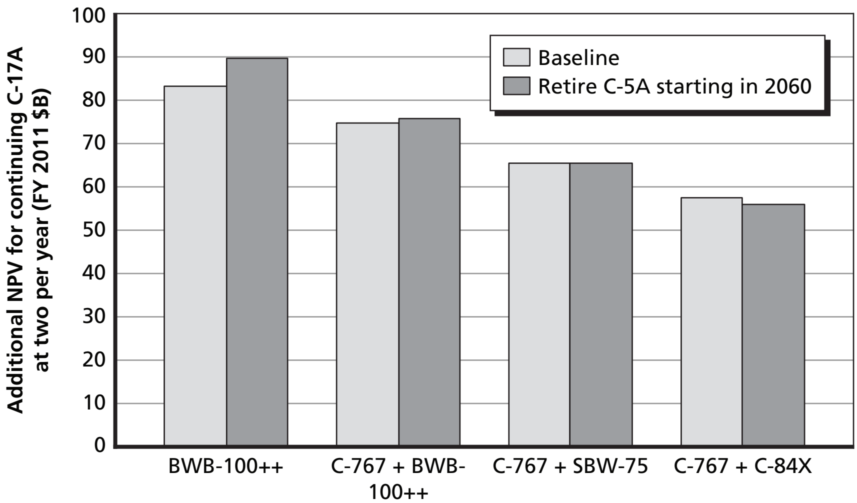
ers, the unit procurement cost would be $444 million.[3] In this option, 40 additional C-17A aircraft are procured to replace all but one C-5A aircraft. Again, this high unit procurement cost would allow C-17A production to continue such that the C-17A line could later be ramped up to full-rate production. We considered this solution only in the context of a transition from low-rate production of two per year to full production once older C-17A aircraft and C-5M aircraft begin to retire. The NPVLCC for this option is $50.3 billion than that for the C-84X in the baseline retirement option. See Figure 6.3.

The additional NPVLCC for continuing C-17A production at two aircraft per year is very similar to the six-aircraft-per-year case. This indicates that continued C-17A production is not cost-effective at any realistic production rate.

Figure 6.3
Additional NPVLCC for Two-per-Year C-17A Continuation Compared to the Most Cost-Effective Aircraft Alternatives



RAND *MG1238-6.3*

3 Based on the production rate results shown in Figure 5.2.

Sensitivity Analyses

Because of uncertainty associated with the aging and viability of the C-5 and C-17A fleet, along with the actual costs of any future program, it was important to analyze the sensitivity of the results of the baseline analysis. Specifically, we examined the sensitivity of the results to changes in BWB-100++ costs. This is an important case to consider because the BWB-100++ provides the greatest cost savings but also presents the greatest technological risk.

Another analysis addressed sensitivity to changes in service life of the C-5 and C-17A inventory. Many aircraft have exceeded their anticipated service life, but the possibility of some catastrophic unknown that could significantly decrease the service life of an aircraft always remains.

A third analysis examined the sensitivity of the results to changes in C-767 procurement costs. This is an important case to study, since the C-767 is the first aircraft procured in three of the four most cost-effective fleet options.

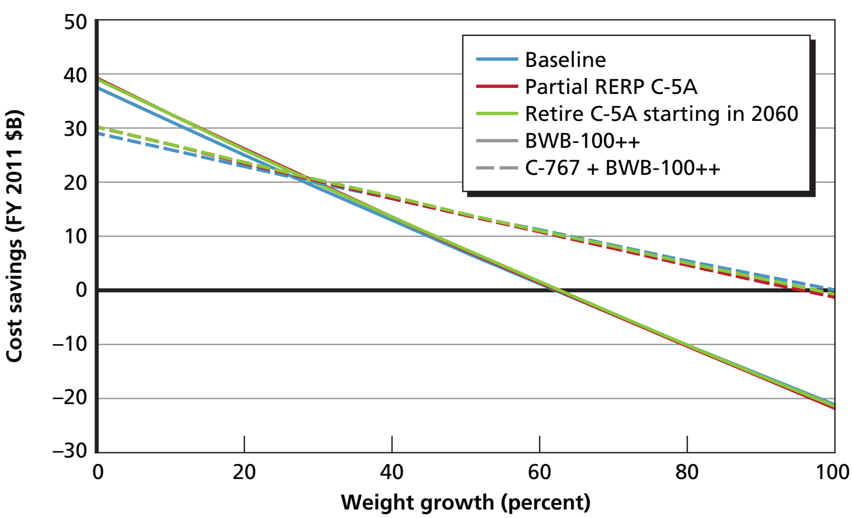
Finally, we examined the sensitivity of C-5A RERP costs. The baseline assumption was that a C-5A RERP has the same costs and resulting effectiveness and availability as a C-5B RERP. However, since the C-5A is significantly less available than the C-5B, it is entirely possible that this assumption is not true and that, in fact, it would cost more to bring a C-5A RERPed aircraft to the same availability and reliability as a C-5B RERPed aircraft.

Sensitivity to BWB-100++ Costs

The BWB-100++ had the greatest cost savings of any fleet alternative. Given the major technological advancements associated with the BWB-100++, it is important to understand how these results could change if program costs increased. Specifically, we assessed cost sensitivity to weight growth. Weight growth increases RDT&E, procurement, and O&S costs. As discussed in Chapter Five, all these costs are a function of aircraft empty weight. At slightly more than 60-percent weight growth, the BWB-100++ no longer offers cost savings over the C-84X. At 27-percent weight growth, it is better to first procure the C-767,

then the BWB-100++, rather than just purchasing the BWB-100++ directly. Therefore, the BWB-100++ should be purchased as part of a single fleet only if the weight growth of the aircraft is less than 27 percent. A 27-percent weight growth corresponds to a 20-percent increase in RDT&E, a 21-percent increase in procurement costs, and an 18-percent in increase in O&S costs (excluding crew and fuel). The relationships between weight growth and both RDT&E cost and procurement cost are based on an update of previous RAND costing models; the relationship between weight growth and O&S cost was derived using the CERs presented in Chapter Five.[4] Note that this analysis assumes the performance of the aircraft remains constant, i.e., that the weight growth did not decrease range or payload capacity. Figure 6.4 shows the effects of weight growth. As the figure shows, at zero weight growth, the C-767 + BWB-100++ has significantly less cost savings; however, this option is significantly less sensitive to BWB-100++ weight

Figure 6.4
Decreased BWB-100++ Cost Savings with Weight Growth



RAND *MG1238-6.4*

4 Timson, 2005.

growth and therefore significantly reduces the financial risk associated with the advanced technology.

While the weight growths shown are very large, it is important to note that the BWB-100++ is a conceptual design at the early phases of experimental flight testing. However, the technology appears promising and would continue to be the most cost-effective option below 26 percent weight growth.

Sensitivity to Service Life of C-5 and C-17A Fleet

We examined the sensitivity of the results to changes in service life of the C-5 and C-17A. To do so, we used the baseline C-5 and C-17A fleet option, then increased and decreased the maximum EFH for each component on the C-5 and the C-17A by 20 percent. Table 6.4 shows the changes in cost savings from the baseline for Category A aircraft alternatives. In all cases, except the BWB-100++, reducing the C-5 and C-17A fleet service life by 20 percent EFH significantly decreases the cost savings, and vice versa for an increase in service life. The BWB-100++ does not follow the trend; in particular, the cost savings decrease if the life expectancy of the C-5 and C-17A fleet increases. This is because the BWB-100++ represents such an improvement in technology and efficiency that the cost savings for bringing the BWB-100++ into service early fully compensate for the earlier expenditures required to do so.

Table 6.4
Cost Savings for Category A Aircraft at Various Service Life Levels

Fleet Alternative	Baseline –20% EFH	Baseline	Baseline +20% EFH
BWB-100 + BWB-100++	–1	9	16
BWB-100++	38	38	37
SBW-75	9	16	21
C-59X	–99	–64	–40
C-84X	–13	0	8
Restart C-17A	–64	–37	–19

NOTES: Amounts in FY 2011 $B. Red cells indicate additional costs.

Table 6.5 shows the same results for mixed fleets of Category A and Category B aircraft alternatives. For all options, decreasing the fleet service life decreases the cost savings, and increasing the fleet service life increases the cost savings. Figure 6.5 illustrates these data for the four most cost-effective fleet options.

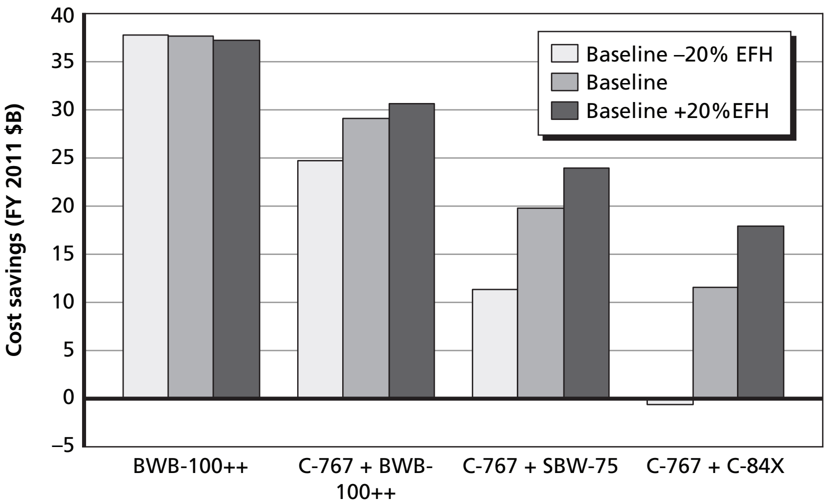
The sensitivity of the most cost-effective options to changes in service life varies inversely to the cost savings of the option, i.e., the

Table 6.5
Cost Savings for Mixed-Fleet Alternatives at Various Service Life Levels

Fleet Alternative	Baseline –20% EFH	Baseline	Baseline +20% EFH
A400M + BWB-100++	–213	–145	–99
A400M + SBW-75	–216	–146	–100
A400M + C-59X	–219	–148	–102
A400M + C-84X	–218	–147	–101
C-17FE + BWB-100++	–69	–39	–21
C-17FE + SBW-75	–72	–41	–22
C-17FE + C-59X	–76	–42	–23
C-17FE + C-84X	–74	–41	–22
C-747 + BWB-100 + BWB-100++	–10	3	12
C-747 + BWB-100++	–3	8	16
C-747 + SBW-75	–11	2	12
C-747 + C-59X	–29	–8	4
C-747 + C-84X	–15	0	10
C-767 + BWB-100 + BWB-100++	6	15	21
C-767 + BWB-100++	25	29	31
C-767 + SBW-75	11	20	24
C-767 + C-59X	–41	–16	–2
C-767 + C-84X	–1	12	18
C-777 + BWB-100 + BWB-100++	3	13	19
C-777 + BWB-100++	16	23	26
C-777 + SBW-75	7	16	22
C-777 + C-59X	–32	–10	4
C-777 + C-84X	–3	10	17

NOTES: Amounts in FY 2011 $B. Red cells indicate additional costs.

Figure 6.5
Cost Savings for Most Cost-Effective Aircraft Alternatives at Various Service Life Levels



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less the cost savings of an option, the more sensitive it is to the change in service life. For example, the BWB-100++ offers a reduction in cost such that replacing the existing fleet early with the BWB-100++ is in fact a net benefit.

Sensitivity to C-5A RERP Cost

We did not explicitly examine the relative availability and reliability of C-5A and C-5B RERPs but instead examined the sensitivity of the results to changes in C-5A RERP cost. Specifically, we assumed that, with additional RERP spending, a C-5A RERP could have the same availability and reliability as a C-5B RERP. As of 2010, the baseline RERP cost is approximately $114 million.[5]

We assessed the break-even cost-effectiveness point for a C-5A RERP for two different retirement options; the first was the baseline,

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[5] U.S. Department of Defense, "Selected Acquisition Report: C-5 RERP," Washington, D.C.: Defense Acquisition Management Information Retrieval, December 31, 2011.

and the second was a 2060 retirement of all C-5As. Therefore, this analysis revealed the C-5A RERP cost at which the baseline is more cost-effective and the C-5A RERP cost at which retiring all C-5As in 2060 is more cost-effective. Table 6.6 shows the cost for a C-5A RERP in which the RERP would be equally as cost-effective as the solution shown. For example, procuring the SBW-75 and following the baseline retirement schedule would be equally as cost-effective as the C-5A RERP option if the C-5A RERP cost were $162 million. Similarly, procuring the C-84X and retiring all C-5A aircraft starting in 2060 would be equally as cost-effective as procuring the C-84X and RERPing 21 C-5As if the C-5A RERP cost were $128 million. Note that, in this table, cells that are less than the baseline RERP cost of $114 million is shaded.

Table 6.6 shows that the highest technology alternative, the BWB-100++, has a break-even C-5A RERP cost of $192 million compared to the baseline case. That is to say, compared to the baseline of keeping all C-5s until they reach the end of their service life, RERPing a portion of the C-5A fleet would be cost-effective if the RERP cost were $192 million or less. This is higher than the $132 million for the SBW-75, which is also higher than the $111 million for the C-84X. This means that the more cost-effective the alternative one plans to

Table 6.6
Break-Even C-5A RERP Cost for Category A Aircraft

Fleet Alternative	Baseline	Retire C-5A Starting in 2060
BWB-100 + BWB-100++	178	111
BWB-100++	192	123
SBW-75	132	112
C-59X	–54	69
C-84X	111	107
Restart C-17A	–37	73

NOTES: Amounts in FY 2011 $M. Shaded cells indicate values lower than the baseline RERP cost of $114 million.

procure, the more one is willing to spend on a C-5A RERP. This is because we assumed that, once a C-5A aircraft was RERPed, it would be flown more and that other existing C-5M aircraft would be flown less, such that the total C-5 FH remained constant. As a result of this shift in FH, the entire C-5 fleet would be replaced earlier. Given this early C-5 recapitalization, the better the alternative replacing the C-5, the less the additional cost. Therefore, the penalty associated with the earlier replacement of the C-5 aircraft is less for the BWB-100++ than it is for the SBW-75 or C-84X, which means that more money can be spent on the C-5A RERP to still have a cost-effective solution.

This observation of the break-even C-5A RERP cost being higher for higher-technology aircraft is less acute when comparing the RERP case with the one in which all C-5As would otherwise have been retired starting in 2060. This is because there is little timing difference in the C-5 fleet replacement between retiring all C-5A starting in 2060 and the C-5A RERP option.

Table 6.7 compares the break-even C-5A RERP cost with the mixed-fleet alternatives. The partial RERP of the C-5As is very unattractive for the A400M and the C-17FE fleet options. This is because both the A400M and C-17FE can carry almost all the cargo, meaning that very few of the follow-on aircraft need to be procured. Because of the low procurement of the follow-on aircraft, the cost of the follow-on aircraft is dominated by R&D, and the cost savings associated with the more advanced alternative are minimal. Since the partial RERP of the C-5A fleet brings the C-5s out of the inventory earlier the flying is spread more evenly across previous C-5As and C-5Bs, the high R&D cost of the follow-on aircraft is moved forward. Again, this is much less acute in comparison to retiring all C-5A aircraft starting in 2060, since the shift in R&D spending is small.

Figure 6.6 shows the results for the break-even C-5A RERP costs for the four most cost-effective fleet alternatives. Again, this chart gives the RERP cost at which doing a partial RERP of the C-5A fleet and retiring the remaining C-5As is equally as cost-effective as either following the baseline (retaining all the C-5As until they reach their service life) or retiring the C-5As starting in 2060. If the C-5A RERP costs less than this break-even, it is cost-effective. In most cases, we are

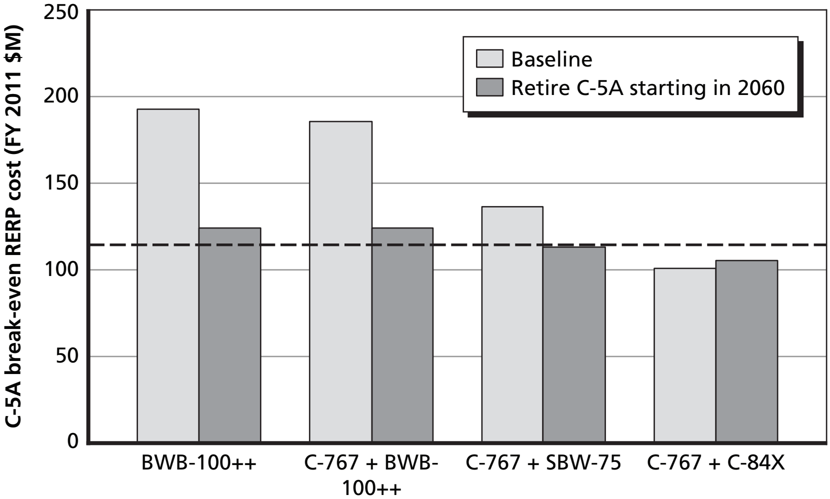
Table 6.7
Break-Even C-5A RERP Cost for Mixed-Fleet Alternatives

Fleet Alternative	Baseline	Retire C-5A Starting in 2060
A400M + BWB-100++	–295	3
A400M + SBW-75	–391	–11
A400M + C-59X	–513	–25
A400M + C-84X	–436	–17
C-17FE + BWB-100++	–151	61
C-17FE + SBW-75	–247	48
C-17FE + C-59X	–369	33
C-17FE + C-84X	–292	42
C-747 + BWB-100 + BWB-100++	176	102
C-747 + BWB-100++	166	106
C-747 + SBW-75	93	90
C-747 + C-59X	–125	52
C-747 + C-84X	75	85
C-767 + BWB-100 + BWB-100++	183	111
C-767 + BWB-100++	185	124
C-767 + SBW-75	136	113
C-767 + C-59X	–88	60
C-767 + C-84X	101	105
C-777 + BWB-100 + BWB-100++	191	119
C-777 + BWB-100++	190	128
C-777 + SBW-75	137	112
C-777 + C-59X	–84	75
C-777 + C-84X	107	111

NOTES: Amounts in FY 2011 $M. Shaded cells indicate values lower than the baseline RERP cost of $114 million.

willing to pay more to RERP the C-5A than the expected RERP cost of $114 million to RERP a C-5B.

Figure 6.6
Break-Even RERP Cost for C-5A Compared to the Baseline Retirement Schedule and to Retiring C-5As Starting in 2060 for the Most Cost-Effective Aircraft Alternatives



NOTE: The dashed line indicates the estimated RERP cost of $114 million.
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Compared to the baseline case, most of the C-5A RERP cases are cost-effective even at significantly higher RERP costs. However, when compared to retiring all the C-5As in 2060, the break-even RERP cost is close to the expected $114 million cost.

Sensitivity to C-767 Procurement Cost

For both the SBW-75 and the C-84X, it is more cost-effective to procure the C-767 first than to buy a pure fleet of either. To understand the sensitivity of these results, we examined the cost at which the C-767 followed by the SBW-75 or C-84X is equally as cost-effective as just procuring the SBW-75 or C-84X, respectively. Given the baseline C-767 procurement cost of $192 million, the C-767 is still the cost-effective option compared to direct procurement of SBW-75 or C-84X at $222 million or $303 million, respectively, for the baseline retirement case. For the option of retiring all C-5As in 2060, the cost

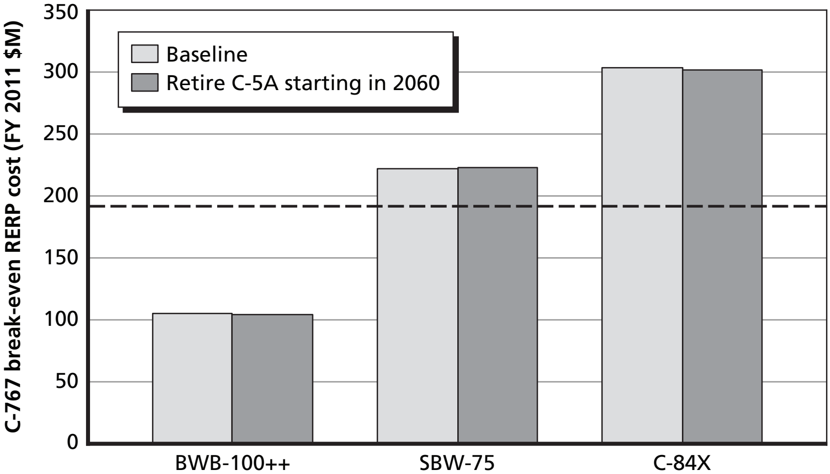
at which the C-767 is still cost-effective is very similar to the baseline retirement cost, with a break-even C-767 procurement cost of $223 million or $301 million for the SBW-75 or C-84X, respectively. Given that the estimated $192 million procurement cost for the C-767 is the aircraft list price of the commercial 767, it is very unlikely that the actual procurement cost would be significantly higher, even once necessary military modifications are included. However, for procurement of the C-767 followed by the BWB-100++ to be more cost-effective than direct procurement of the BWB-100++, the C-767 procurement cost would need to be less than $106 million for the baseline retirement option or $104 million for the retiring all C-5As in 2060 option. Given the $192 million list price of the commercial 767, it is unlikely that a militarized version of the 767 would be procured at these prices. However, even though the C-767 followed by the BWB-100++ is not as cost-effective as a fleet of only BWB-100++, it may still be necessary to purchase the C-767 first because the BWB-100++ technology may not be matured in time. See Figure 6.7.

The fact that the break-even C-767 for the BWB-100++ is less than the $192 million list price indicates that it is better to procure the BWB-100++ alone and not as part of a mixed fleet. However, for both the SBW-75 and the C-84X, the break-even C-767 cost is above the $192 million list price, meaning that both aircraft are better as part of a mixed fleet. In the case of the SBW-75, this conclusion would change if the cost of the C-767 increased 16 percent; however, the C-84X is more cost-effective as part of a mixed fleet with the C-767 even at significantly higher C-767 costs.

Sensitivity to Continued C-17A Procurement Cost

In this option, 41 additional C-17A aircraft are procured to replace the entire fleet of C-5A aircraft. A C-17A is roughly equivalent to a C-5A in terms of capability; a C-5A has double the cargo capacity and room for additional PAX but less than one-half the availability. Assuming that Boeing sells an additional five aircraft per year to foreign partners, the unit procurement cost would be $294 million. For all fleet alternatives in both the baseline retirement schedule and retiring C-5As starting in 2060, the continued procurement of C-17As and replacement of C-5As

Figure 6.7
Break-Even C-767 Procurement Cost for Mixed-Fleet Options Compared to Corresponding Single-Fleet Option



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is never cost-effective. Specifically, for the option to be cost-effective, the unit procurement cost for a C-17A would always have to be less than $294 million. This option looks most attractive if the fleet alternative is an A400M followed by a C-59X and if all C-5As are retired starting in 2060, and even then, the C-17A procurement cost would need to be less than $192 million. Tables 6.8 and 6.9 show the C-17A procurement cost for break-even cost-effectiveness versus Category A aircraft and mixed-fleet alternatives, respectively.

Figure 6.8 shows that, for the four most cost-effective aircraft alternatives, the C-17A procurement cost would have to be no more than $58 million for the continued C-17A production at ten per year and replacement of C-5As to be cost-effective. Given that this price is simply unrealistic, the continued C-17A production at ten per year is never cost-effective.

Like the other C-17A continuation cases considered, the break-even cost for the C-17A at ten aircraft per year is significantly lower than the expected price of the C-17A. This again indicates that C-17A

Table 6.8
Break-Even C-17A Continuation Cost for Category A Aircraft

Fleet Alternative	Baseline	Retire C-5A Starting in 2060
BWB-100 + BWB-100++	58	20
BWB-100++	47	8
SBW-75	43	32
C-59X	36	106
C-84X	45	42
Restart C-17A	40	103

NOTES: Amounts in FY 2011 $M. Continuation is for ten per year. Shading indicates break-even costs are less than the $294 million C-17A cost.

continuation is not cost-effective even if the procurement cost could be decreased slightly.

Sensitivity to Reduced Requirement Level

As discussed earlier, after we completed our research, Congress enacted the Budget Control Act of 2011. Among other things, this caused a shift in national security strategy to reflect a reduced budget. The National Defense Authorization Act for Fiscal Year 2012, signed into law on December 31, 2011, allowed the retirement of additional C-5As beyond the planned retirements considered here. In particular, the act approved a reduction to 27 C-5As. It was reported in March 2012 that the Air Force was requesting from Congress the authority to retire all the remaining C-5As.[6] The justification for this request was based on the strategic guidance no longer requiring the military to fight two near-simultaneous large-scale land wars. This previous requirement aligned with MCRS-16 Case 1, the case we used; however, the new strategic guidance better aligns itself with a different case.

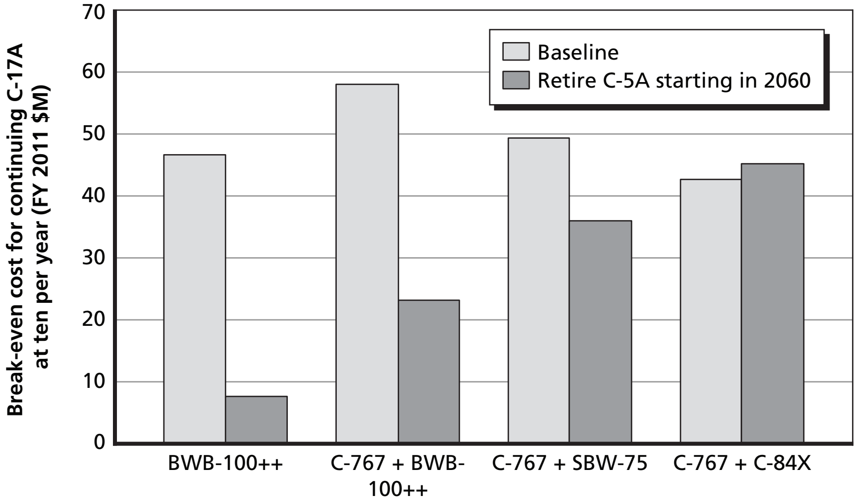
[6] "Air Force Requests C-5 Retirement Authority, Predicts $1 Billion in Savings," *Inside Defense*, March 16, 2012.

Table 6.9
Break-Even C-17A Continuation Cost for Mixed-Fleet Alternatives

Fleet Alternative	Baseline	Retire C-5A Starting in 2060
A400M + BWB-100++	–51	118
A400M + SBW-75	–78	139
A400M + C-59X	–105	172
A400M + C-84X	–91	147
C-17FE + BWB-100++	–18	103
C-17FE + SBW-75	–45	123
C-17FE + C-59X	–72	156
C-17FE + C-84X	–59	131
C-747 + BWB-100 + BWB-100++	75	32
C-747 + BWB-100++	70	36
C-747 + SBW-75	53	51
C-747 + C-59X	–3	98
C-747 + C-84X	49	54
C-767 + BWB-100 + BWB-100++	65	25
C-767 + BWB-100++	58	23
C-767 + SBW-75	49	36
C-767 + C-59X	7	91
C-767 + C-84X	43	45
C-777 + BWB-100 + BWB-100++	67	26
C-777 + BWB-100++	61	26
C-777 + SBW-75	52	39
C-777 + C-59X	1	91
C-777 + C-84X	44	46

NOTES: Amounts in FY 2011 $M. Continuation is for ten per year. Shading indicates break-even costs are less than the $294 million C-17A cost

Figure 6.8
Break-Even Cost for Ten-per-Year C-17A Continuation for the Most Cost-Effective Aircraft Alternatives



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As a simple excursion, we modified our results for a lower requirement level, defined as 104 MC C-5M equivalents. This is 13 MC C-5M equivalents lower than the original requirement, or about an 11 percent reduction in the lift capacity. It is important to note that this is simply an excursion and does not represent a complete analysis of the requirement level, particularly because this reduction is modeled simply as a reduction in the number of MC C-5M equivalents required, without regard to possible changes in routes, timing, and cargo. Table 6.10 shows that, with the reduced requirement level, the savings for the various fleet alternatives are virtually unchanged. Although the savings associated with each alternative are virtually unchanged compared to the baseline C-84X, the total NPV cost is reduced on average $27 billion. The standard deviation of this difference is slightly under $3 billion over all cases. This shows that changes in requirement level produce large changes in total cost but little change in the cost differences among fleet alternatives. Therefore, our results appear robust across requirement levels.

Table 6.10
Cost Savings for Category A Aircraft at a Reduced Requirement

Fleet Alternative	Baseline	Baseline Reduced
BWB-100 + BWB-100++	9	9
BWB-100++	38	37
SBW-75	16	16
C-59X	–64	–61
C-84X	0	0
Restart C-17A	–37	–35

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs.

Table 6.11 shows similar results for mixed fleets. Again, there is very little difference between the savings for the baseline case and those for the reduced retirement case. Figure 6.9 summarizes these results for the four most cost-effective fleet options.

The conclusions presented in this document are insensitive to a reduction in the airlift requirement. The cost savings associated with the BWB-100++ and with mixed fleets involving the C-767 are virtual unchanged with a reduced requirement level. Although the cost savings of the various options are unchanged, the total fleet cost would, of course, be less with a reduced requirement.

Sensitivity to Fuel Prices

We assumed a fuel price of $2.57, based on the KC-X Tanker Modernization Program Request for Proposals. However, there are many reasons to believe that fuel costs will be significantly higher in the future. In fact, the Energy Information Administration's 2011 energy report suggests the price of jet fuel may more than double by 2035 in real dollars.[7] To examine the sensitivity of the results to jet fuel prices, we examined the effects of both doubling and tripling fuel prices. In fact,

[7] U.S. Energy Information Administration, *Annual Energy Outlook 2011*, April 2011.

Table 6.11
Cost Savings for Mixed-Fleet Alternatives at a Reduced Requirement

Fleet Alternative	Baseline	Baseline Reduced
A400M + BWB-100++	–145	–137
A400M + SBW-75	–146	–141
A400M + C-59X	–148	–144
A400M + C-84X	–147	–142
C-17FE + BWB-100++	–39	–41
C-17FE + SBW-75	–41	–44
C-17FE + C-59X	–42	–47
C-17FE + C-84X	–41	–45
C-747 + BWB-100 + BWB-100++	3	5
C-747 + BWB-100++	8	10
C-747 + SBW-75	2	3
C-747 + C-59X	–8	–11
C-747 + C-84X	0	1
C-767 + BWB-100 + BWB-100++	15	16
C-767 + BWB-100++	29	29
C-767 + SBW-75	20	19
C-767 + C-59X	–16	–18
C-767 + C-84X	12	11
C-777 + BWB-100 + BWB-100++	13	13
C-777 + BWB-100++	23	23
C-777 + SBW-75	16	16
C-777 + C-59X	–10	–12
C-777 + C-84X	10	9

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs.

the results were extremely robust to increased fuel prices. Table 6.12 shows how fuel prices affect cost savings for Category A aircraft. As the

Figure 6.9
Cost Savings for Most Cost-Effective Aircraft Alternatives at a Reduced Requirement

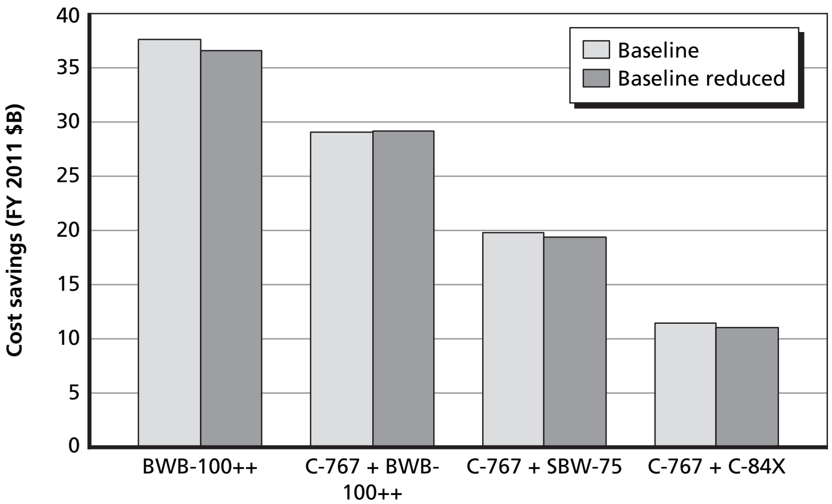

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Table 6.12
Cost Savings for Category A Aircraft at Increased Fuel Prices

		Fuel Price	
Fleet Alternative	**Baseline**	**Double**	**Triple**
BWB-100 + BWB-100++	9	13	17
BWB-100++	38	45	52
SBW-75	16	18	19
C-59X	–64	–72	–81
C-84X	0	0	0
Restart C-17A	–37	–46	–54

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs.

table shows, the savings increase for the three cost-saving options. In particular, the savings are greatest for the most cost-saving options and vice versa for the more costly options.

Table 6.13 shows how fuel prices affect cost savings for mixed-fleet options. Again, other than a few cases in which the savings or additional costs are near zero, fleet alternatives with savings have increased

Table 6.13
Cost Savings for Mixed-Fleet Aircraft at Increased Fuel Prices

		Fuel Price	
Fleet Alternative	**Baseline**	**Double**	**Triple**
A400M + BWB-100++	–145	–150	–154
A400M + SBW-75	–146	–152	–156
A400M + C-59X	–148	–153	–158
A400M + C-84X	–147	–152	–157
C-17FE + BWB-100++	–39	–45	–50
C-17FE + SBW-75	–41	–46	–52
C-17FE + C-59X	–42	–48	–54
C-17FE + C-84X	–41	–47	–52
C-747 + BWB-100 + BWB-100++	3	3	3
C-747 + BWB-100++	8	8	8
C-747 + SBW-75	2	2	1
C-747 + C-59X	–8	–11	–13
C-747 + C-84X	0	–1	–2
C-767 + BWB-100 + BWB-100++	15	18	21
C-767 + BWB-100++	29	33	38
C-767 + SBW-75	20	21	23
C-767 + C-59X	–16	–19	–22
C-767 + C-84X	12	12	14
C-777 + BWB-100 + BWB-100++	13	15	18
C-777 + BWB-100++	23	26	29
C-777 + SBW-75	16	18	19
C-777 + C-59X	–10	–12	–13
C-777 + C-84X	10	11	12

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs.

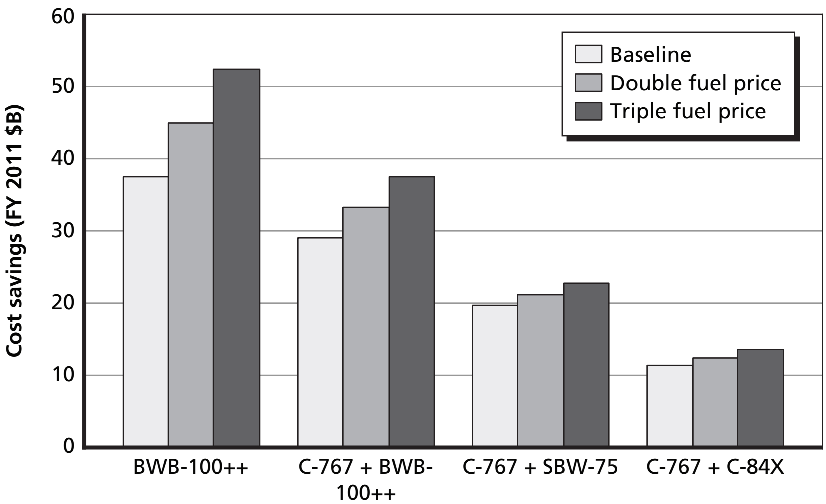
savings with increased fuel price and vice versa for more costly options. Figure 6.10 shows the effect of fuel prices on cost savings for the four most cost-effective options.

In general, the more cost-effective alternatives are even more cost-effective with increased fuel prices, and the least cost-effective alternatives are even less cost-effective with increased fuel prices. This is as expected, since the most cost-effective alternatives tend to have the best fuel economy and vice versa.

Sensitivity to Life Span of Future Aircraft

Our baseline assumption was a 30-year life span for future aircraft. This is consistent with an initial C-17A life expectancy of 30,000 hours, which, at 1,000 hours per year, corresponds to 30 years. However, the C-17A is now expected to reach 45,000 flight hours; again, at 1,000 hours per year, this corresponds to 45 years. Given the possibility of the C-17A life being extended even further and given the age of the C-5 fleet, the possibility of the future fleet aging to 60 years is plausible.

Figure 6.10
Cost Savings for Most Cost-Effective Aircraft Alternatives at Increased Fuel Prices



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Therefore, we examined the sensitivity of the results to changes in life expectancy. Table 6.14 shows that the results are very robust to changes in life span. In particular, options with cost savings have greater cost savings than the baseline; more costly options have greater costs.

Table 6.15 shows the same results but for mixed-fleet options. Again, the solutions are very robust. In particular, excluding a few cases with near-zero cost savings, the cases with cost savings have greater cost savings with longer life spans, and the options with additional costs have even higher costs with longer life spans. These tables show that, even if the future fleet lasts longer than 30 years, our results are robust. Figure 6.11 shows how the life span of follow-on aircraft affects cost savings for the four most cost-effective options.

Obviously, as the life span of the future aircraft alternatives is increased the cost savings also increase. The increase in cost savings is greatest for the alternatives with the highest RDT&E and procurement cost, such as the BWB-100++.

Parametric Analyses

For several of our cases, we were unable to obtain reliable and detailed cost information. This was true for both the An-124 and the Il-76, so

Table 6.14
Cost Savings for Category A Aircraft at Increased Life Span

		Life Span	
Fleet Alternative	**Baseline**	**45 Years**	**60 Years**
BWB-100 + BWB-100++	9	13	17
BWB-100++	38	45	52
SBW-75	16	18	19
C-59X	–64	–72	–81
C-84X	0	0	0
Restart C-17A	–37	–46	–54

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs.

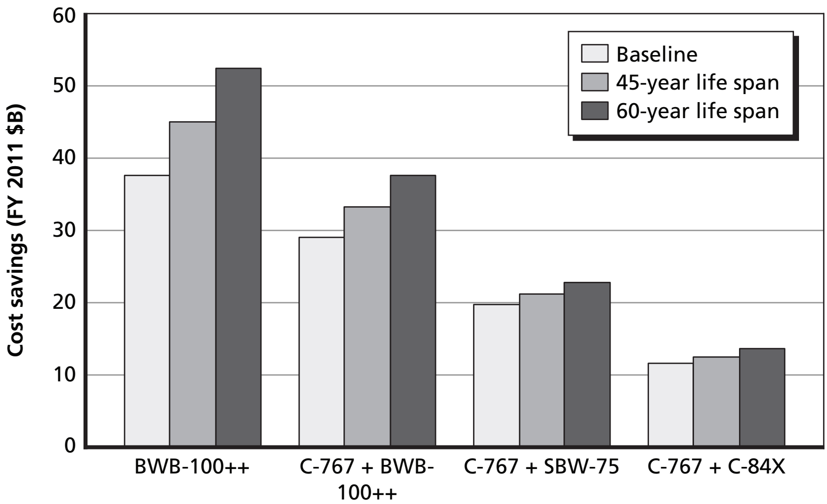
Table 6.15
Cost Savings for Mixed-Fleet Aircraft at Increased Life Span

		Life Span	
Fleet Alternative	**Baseline**	**45 Years**	**60 Years**
A400M + BWB-100++	–145	–150	–154
A400M + SBW-75	–146	–152	–156
A400M + C-59X	–148	–153	–158
A400M + C-84X	–147	–152	–157
C-17FE + BWB-100++	–39	–45	–50
C-17FE + SBW-75	–41	–46	–52
C-17FE + C-59X	–42	–48	–54
C-17FE + C-84X	–41	–47	–52
C-747 + BWB-100 + BWB-100++	3	3	3
C-747 + BWB-100++	8	8	8
C-747 + SBW-75	2	2	1
C-747 + C-59X	–8	–11	–13
C-747 + C-84X	0	–1	–2
C-767 + BWB-100 + BWB-100++	15	18	21
C-767 + BWB-100++	29	33	38
C-767 + SBW-75	20	21	23
C-767 + C-59X	–16	–19	–22
C-767 + C-84X	12	12	14
C-777 + BWB-100 + BWB-100++	13	15	18
C-777 + BWB-100++	23	26	29
C-777 + SBW-75	16	18	19
C-777 + C-59X	–10	–12	–13
C-777 + C-84X	10	11	12

NOTE: Amounts in FY 2011 $B. Red cells indicate additional costs.

we treated these aircraft parametrically to find the cost at which they would be cost-effective. The same is true for a C-17A SLEP; as of 2012, no particular SLEP program has been identified and no reasonably

Figure 6.11
Cost Savings for Most Cost-Effective Aircraft Alternatives at Increased Life Span



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accurate estimates for the SLEP cost or the resulting increase in service life exist.

Finally, we examined the procurement cost at which continuing the C-17A line would be cost-effective. This is useful because it provides a context for determining how close the C-17A is to being cost-effective and whether or not any program changes could produce significant enough program cost reductions to make the aircraft cost-effective.

Cost-Effectiveness of An-124 and Il-76

There are inherent problems with purchasing and operating aircraft manufactured by a country that is not a close ally of the United States. Therefore, to the extent that these aircraft may be cost-effective, other problems may render these aircraft unsuitable for the United States. These problems include, but are not limited to, availability of spare parts, cost uncertainties, technology transfer restrictions, and ongoing airworthiness compliance. It is plausible for spare parts for these aircraft to be delayed during peacetime and withheld during conflicts.

Since the manufacturers would not be subject to Defense Contract Audit Agency oversight, price gouging during times of crisis or perceived reliance may occur.

Since pricing data for the An-124 and Il-76 are not readily available, we performed a parametric analysis. The An-124 is a Category A aircraft, meaning that it is capable of carrying all required cargo. The Il-76 is a Category B aircraft, so it would need to be followed by a Category A aircraft. For the analysis, we calculated the cost at which the An-124 and Il-76 options are equally as cost-effective as other options for the baseline retirement schedule. We assumed that the An-124 and Il-76 would be equally as available as the C-17A, at 73 percent. The An-124 was cost-effective compared to the BWB-100++ at a procurement cost of $341 million. Similarly, the An-124 was cost-effective compared to the C-767 followed by the BWB-100++, SBW-75, or C-84X at a procurement cost of $426 million, $524 million, or $608 million, respectively. Although the actual procurement cost of an An-124 is unknown, it is likely to be less than $341 million.[8] Therefore, the An-124 is likely to be the most cost-effective option. The fundamental reason that the An-124 appears so cost-effective is that it is the right size aircraft (C-5-sized) and has no associated RDT&E costs or learning curve. The Il-76, on the other hand, is not cost-effective. In most cases, the procurement cost for the Il-76 would need to be negative, meaning that the manufacturer would have to pay to sell the aircraft. Compared to the C-767 followed by the C-84X, the procurement cost for the Il-76 would need to be less than $5 million for the aircraft to be cost-effective, which is an impossible price. Therefore, the Il-76 is never a cost-effective option. Table 6.16 lists these results, and Figure 6.12 shows the break-even procurement costs for the An-124 for both the baseline retirement schedule and for retiring all C-5As starting in 2060. In the case of retiring all C-5As starting in 2060, the break-even cost for the An-124 is approximately $9 million lower than the baseline retirement schedule; this is because retiring C-5As

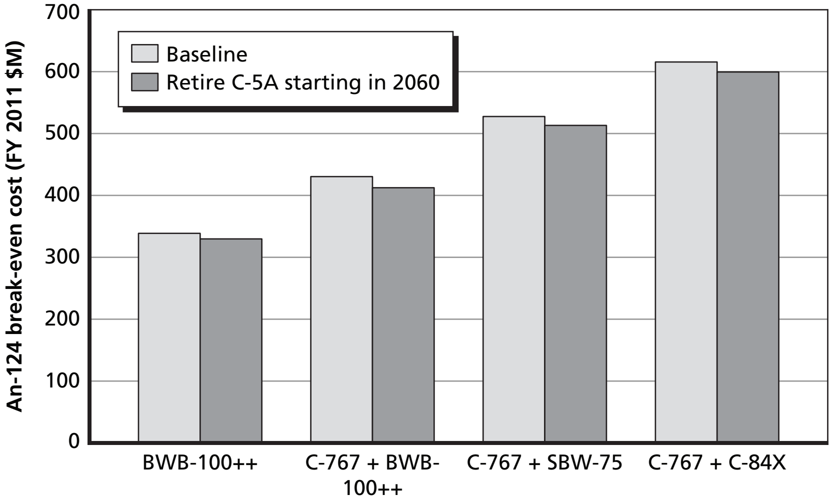
[8] There is no single reputable source for An-124 cost data; however, sources the authors have reviewed indicate a cost less than $200 million. This is significantly less than $341 million, even with substantial cost growth.

Table 6.16
Break-Even Procurement Cost for An-124 and Il-76 for the Baseline Retirement Schedule

Fleet Alternative	BWB-100++	C-767 + BWB100++	C-767 + SBW75	C-767 + C-84X
An-124	341	433	530	617
Il-76 + BWB-100++	–89	–52		
Il-76 + C-84X				5
Il-76 + SBW-75			–24	

NOTE: Amounts in FY 2011 $M. Red cells indicate additional costs.

Figure 6.12
Break-Even An-124 Procurement Cost



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with remaining flight hours is less attractive when the aircraft is being replaced by an aircraft of similar capability and technology, i.e., retiring the C-5As before the end of their service life makes the most sense when they are being replaced with a superior aircraft.[9]

[9] Assuming that service life is defined by flight hours and not by other age-related issues.

Given that an availability of 73 percent is most likely higher than what can be expected of an An-124, we calculated the break-even An-124 procurement cost as a function of availability (Figure 6.13). For lower availabilities, such as 50 percent, the An-124 cost would need to be significantly lower to still be cost-effective, especially when compared to the more advanced technology SBW-75 and BWB-100++.

Even with low availability rates, the An-124 could be a cost-effective option. This means that the An-124 is likely a cost-effective option; however, there are still significant problems associated with the procurement of such a platform.

Cost-Effectiveness of C-17A SLEP

We also examined the cost-effectiveness of a C-17A SLEP parametrically. In particular, we calculated the cost at which a SLEP of the C-17A from 45,000 to 60,000 EFH service life would be cost-effective for a given retirement schedule and fleet alternative. As of 2012, there is no reasonable estimate for SLEP costs. Table 6.17 presents our results for Category A aircraft and Table 6.18 for mixed-fleet

Figure 6.13
Break-Even An-124 Procurement Cost as a Function of Aircraft Availability

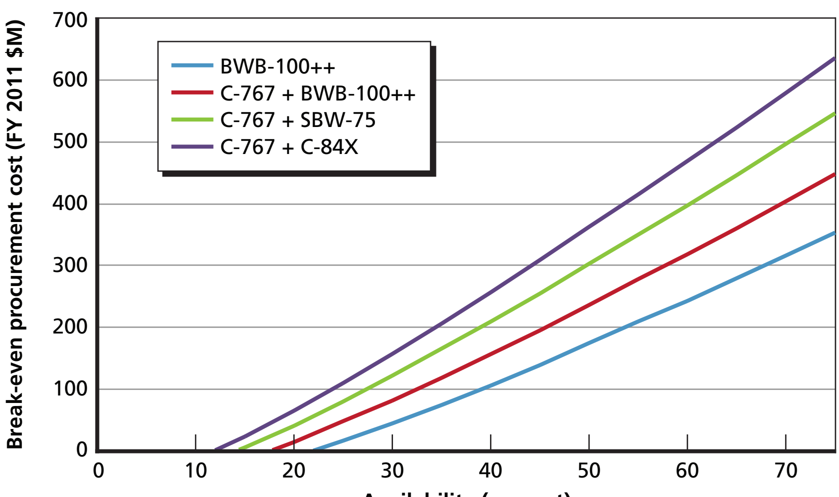

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Table 6.17
Break-Even C-17A SLEP Cost for Category A Aircraft

Fleet Alternative	Baseline
BWB-100 + BWB-100++	95
BWB-100++	5
SBW-75	75
C-59X	321
C-84X	128
Restart C-17A	224

NOTE: Amounts in FY 2011 $M.

alternatives. Table 6.17 shows that the greater the fleet alternative cost savings, as given in Table 6.1, the lower the C-17A SLEP break-even cost. This makes sense, since the C-17A SLEP pushes out the procurement of the new alternative by 15 years; this delay is more valuable when the fleet alternative is more inferior, and vice versa. This trend is also true for mixed-fleet alternatives as given in Table 6.18.

Figure 6.14 shows these results for the most cost-effective fleet alternatives. A C-17A SLEP is equally cost-effective as these most cost-effective fleet alternatives given the baseline retirement schedule at a cost between $7 million and 58 million, depending on the fleet alternative chosen. In the case of a single military airlifter buy, the C-17A SLEP pushes out the RDT&E for the new buy by 15 years. However, since the BWB-100++ represents such a drastic technological improvement, there is little benefit to pushing the procurement out; the C-17A SLEP is therefore only cost-effective below $7 million. In the case of a buy involving the C-767, a C-17A SLEP pushes the RDT&E for the follow-on new-design airlifter out only eight years, which diminishes the overall value of a C-17A SLEP. The break-even C-17A SLEP is an inverse function of the cost savings for the follow-on new-design aircraft. The break-even SLEP cost for the C-17A compared to the C-767 followed by the BWB-100++, SBW-75, or C-84X is $9 million, $35 million, or $58 million, respectively.

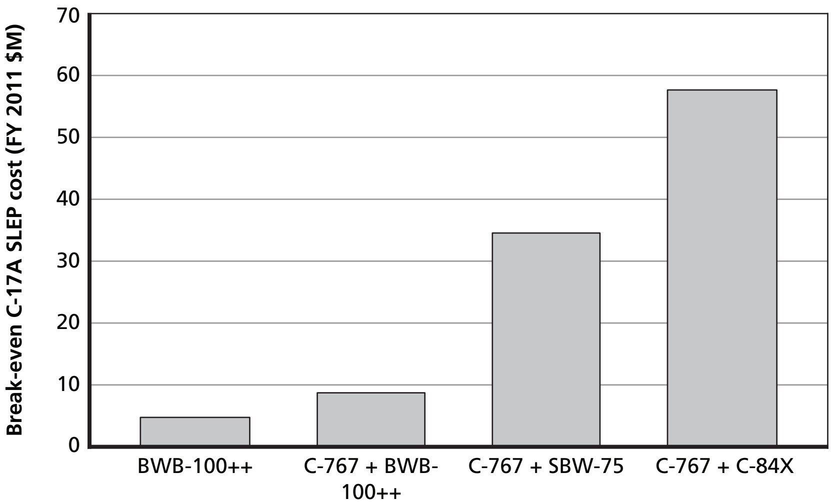
Table 6.18
Break-Even C-17A SLEP Cost for Mixed-Fleet Alternatives

Fleet Alternative	Baseline
A400M + BWB-100++	523
A400M + SBW-75	523
A400M + C-59X	523
A400M + C-84X	523
C-17FE + BWB-100++	227
C-17FE + SBW-75	227
C-17FE + C-59X	227
C-17FE + C-84X	227
C-747 + BWB-100 + BWB-100++	104
C-747 + BWB-100++	85
C-747 + SBW-75	101
C-747 + C-59X	129
C-747 + C-84X	108
C-767 + BWB-100 + BWB-100++	57
C-767 + BWB-100++	9
C-767 + SBW-75	35
C-767 + C-59X	139
C-767 + C-84X	58
C-777 + BWB-100 + BWB-100++	67
C-777 + BWB-100++	29
C-777 + SBW-75	48
C-777 + C-59X	126
C-777 + C-84X	67

NOTE: Amounts in FY 2011 $M.

The decision to SLEP the C-17A of course depends on the SLEP cost, but also depends highly on the future airlift fleet. If, for example, the BWB-100++ is planned, then a C-17A SLEP is likely not cost-

Figure 6.14
Break-Even C-17A SLEP Cost for the Most Cost-Effective Aircraft Alternatives



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effective. However, if a lower-technology option, such as the C-767 followed by the C-84X, is planned then the C-17A SLEP may be cost-effective.

Annual Expenditures Analysis

In addition to NPVLCC savings, we also looked at annual expenditures, which helped us understand spending peaks. Although not quantified, given two spending profiles with the same NPVLCC, the one with the lowest peak annual spending would be preferable. To the extent that steady spending profiles have additional value, a solution with a higher NPVLCC may even be preferable.

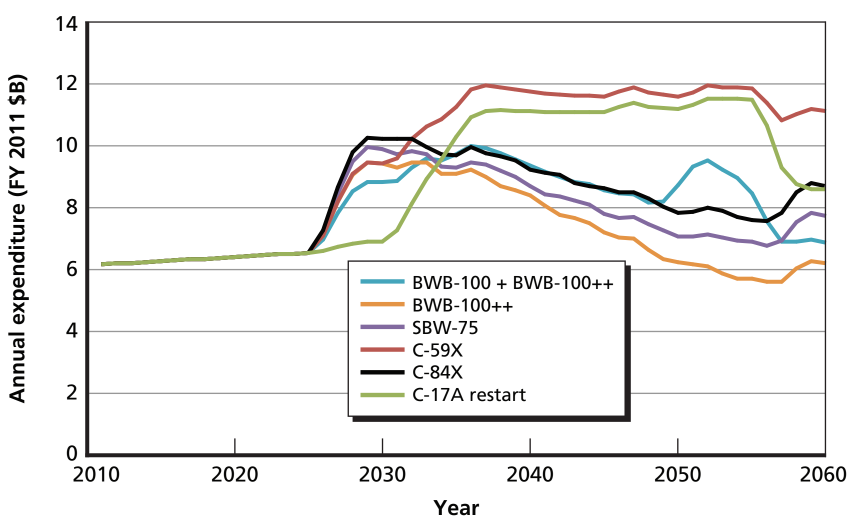
Of course, the Air Force can and does manage the budget peaks of individual programs while maintaining relatively smooth overall budget levels. Despite this ability to manage them, these budget peaks often require deconfliction between multiple important programs,

which can often result in suboptimal timing. Therefore, to the extent that an individual program can minimize its peak spending, it is easier for budgeters to incorporate that program into the overall budget.

To examine the annual spending profiles, we smoothed the retirement profiles from Chapter Two. This prevented essentially random annual fluctuations in the retirement profile from manifesting themselves as large peaks and valleys in spending. This smoothing function is what would happen with normal fleet management, since any procurement program would have a smooth procurement rate. For the purposes of understanding the annual spending profiles, we used the baseline retirement profile; however, since we examined annual spending only out to 2060, these spending profiles are the same as those for the C-5A retirement starting in 2060 option. The spending profiles exclude near-term expenditures for the procurement of C-17A aircraft, up to the scheduled fleet of 221, and the modifications of the C-5B fleet.

Figure 6.15 shows annual expenditures that our model produced for all Category A aircraft. The C-59X is clearly an inferior option

Figure 6.15
Annual Expenditure for Category A Aircraft Alternatives



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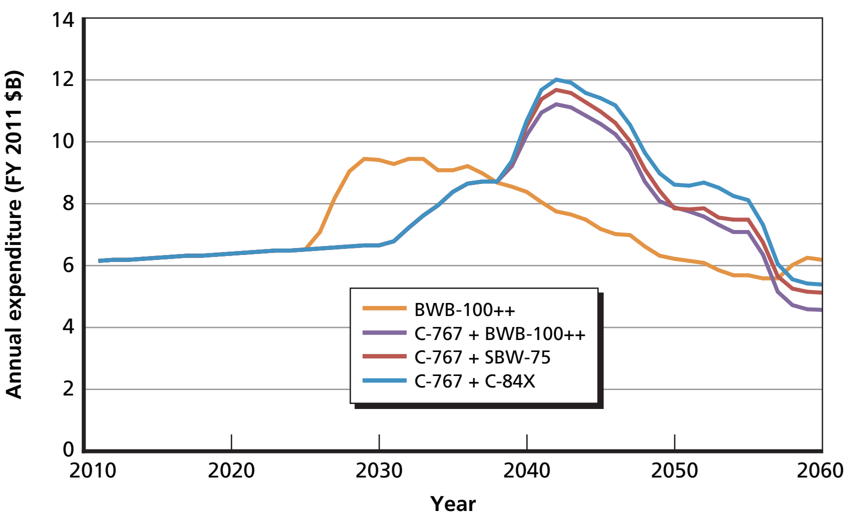
because it has the highest peak spending and the highest NPVLCC. The C-17A restart is also inferior, with the second-highest peak spending and high NPVLCC. The BWB-100 plus BWB-100++ option is clearly inferior to direct purchase of the BWB-100++; purchasing the smaller BWB-100 first provides lower spending only from 2026 to 2032 because of the lower RDT&E cost associated with the smaller BWB design. After that initial period of lower spending, the BWB-100 plus BWB-100++ option is consistently more expensive than just the BWB-100++ option. The BWB-100++, SBW-75, and C-84X each follow similar spending profiles, with the BWB-100++ having the lowest annual spending, followed by the SBW-75; the C-84X has the highest annual spending of the three aircraft. This is consistent with the findings that, of the three aircraft, the BWB-100++ offers the greatest NPVLCC savings.

Among the mixed-fleet options, the three most cost-effective in terms of NPVLCC were the C-767, followed by either the BWB-100++, the SBW-75, or the C-84X. Figure 6.16 shows the annual expenditures for these, adding the BWB-100++ for comparison. Even though the

Figure 6.16
Annual Expenditure for the Most Cost-Effective Aircraft Alternatives



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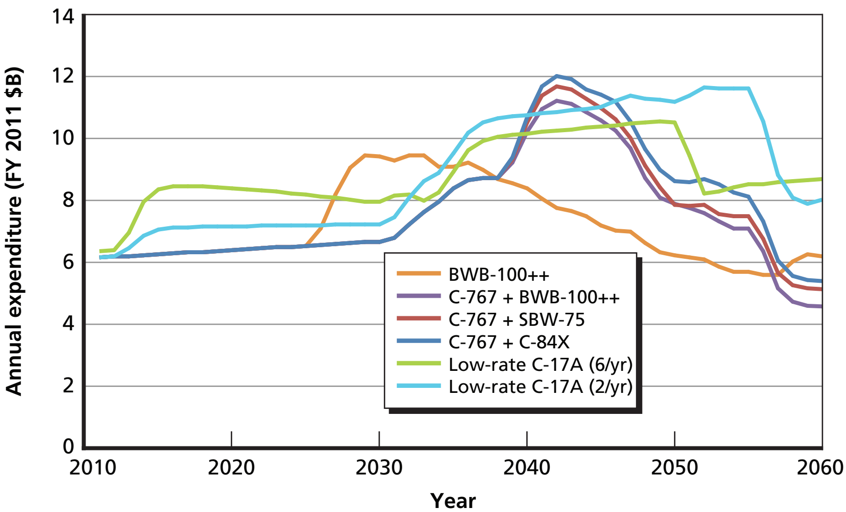
C-767 followed by the SBW-75 or the C-84X has lower NPVLCC than the SBW-75 or the C-84X alone, respectively, there is still a significant spending peak for the C-767 options around 2042. This large peak comes from the fact that, with the C-767 option, C-767 aircraft are being procured at the same time the RDT&E program for the follow-on airlifter is going on. This means that these options have a period of both procurement spending and significant RDT&E spending. Although the peak associated with the C-767 options is higher, the annual expenditures are lower than even the BWB-100++ until 2038.

One of the motivating factors for looking at continued C-17A production was the avoidance of RDT&E costs associated with a new-design aircraft. In particular, procuring C-17A aircraft now at a slow rate allows the production line to be ramped up when large-scale purchases are needed to maintain the fleet. Figure 6.17 shows the annual expenditures for the four most cost-effective options and the two low-rate C-17A production options. In particular, since the C-17A is a current-technology aircraft, it is reasonable to compare it with the

Figure 6.17
Annual Expenditure for the Most Cost-Effective Aircraft Alternatives and Low-Rate C-17A Production Options



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current-technology option of the C-767 followed by the C-84X. Both low-rate C-17A production options have significantly higher annual expenditures than the C-767 + C-84X option, except for brief periods between 2040 and 2047 for the six-per-year rate and between 2041 and 2046 for the two-per-year rate. Given the significantly higher NPVLCC associated with the low-rate C-17A production, these options provide little in terms of annual expenditure decreases.

As mentioned earlier, the primary reason for the large peak associated with the C-767 option is the concurrent procurement of C-767 aircraft and the RDT&E for the follow-on airlifter. It is possible to deconflict these two programs by purchasing C-767 at a slightly faster rate and stopping procurement before executing the RDT&E program, then procuring the follow-on airlifter. This option means retiring some C-17A aircraft a few years earlier and replacing them with C-767 aircraft. This deconfliction option has a slightly higher NPVLCC of $1.4 billion because of the earlier retirement of C-17A aircraft. This increase is the same regardless of which follow-on airlifter is procured because the deconfliction only involves moving the C-767 procurement forward, leaving the follow-on airlifter procurement unchanged. Comparing the three C-767 deconfliction options to the low-rate C-17A production, the C-767 deconfliction option yields only a few years of higher spending; the spending profile is significantly steadier and the NPVLCC significantly lower. The spending profiles for these options are shown in Figure 6.18.

Figure 6.19 compares the three C-767 options for both the regular procurement schedule and the deconflicted procurement schedule, along with the BWB-100++ and the two low-rate C-17A production options. The text alongside each bubble gives the name of the option and the year in which the peak occurs. The BWB-100++ is the best option in all respects. However, among the C-767 options and to the extent that lower annual peak spending is important, the deconfliction option provides significantly lower peak spending, with only a slight reduction in overall cost savings (again, regardless of the follow-on fleet). Both low-rate C-17A production options have a significant cost and do little to decrease peak spending.

Figure 6.18
Annual Expenditure for C-767 Deconfliction Options and for Low-Rate C-17A Production Options

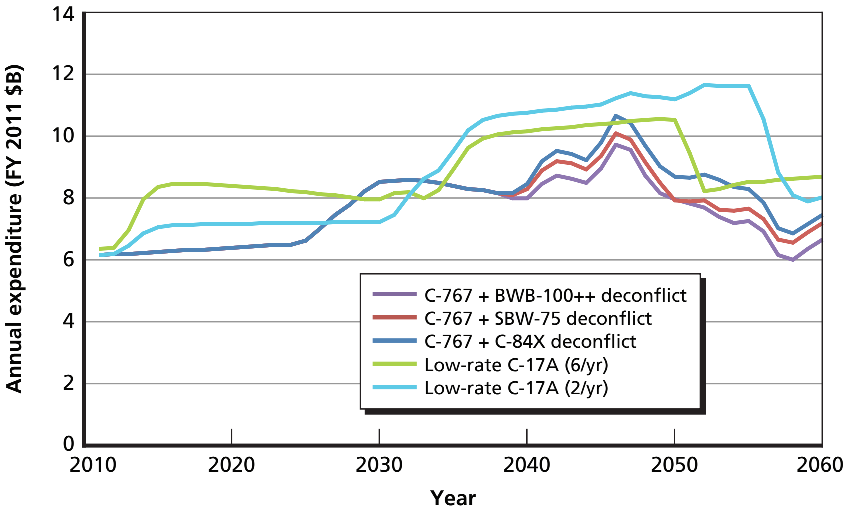

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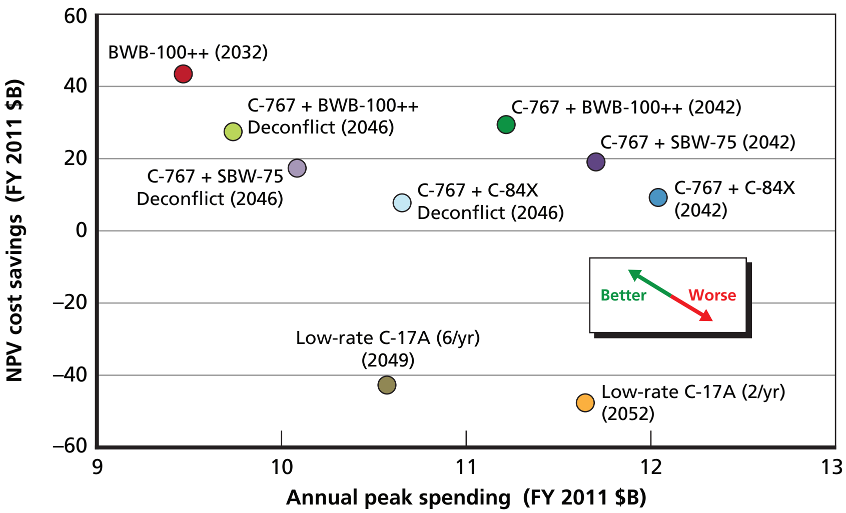
Figure 6.19
Comparison of NPVLCC Savings and Annual Peak Spending for the Most Cost-Effective Solutions and for Two Low-Rate C-17A Production Options



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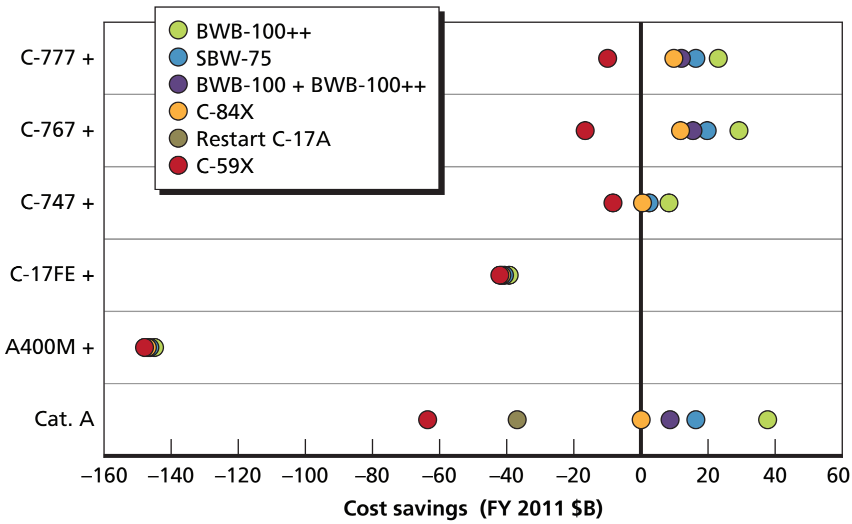
CHAPTER SEVEN

Conclusions

This chapter presents our overall fleet and retirement schedule conclusions. Figure 7.1 shows the alternative fleets we considered in the cost-effectiveness analysis. The fleets shown to the left of the solid black line are not cost-effective for the baseline drawdown and C-5 and C-17A fleet permutations. The bottom row is Category A aircraft, consisting of only one aircraft type, which is indicated by the color. The second row from the bottom is an A400M followed by another aircraft, again indi-

Figure 7.1
Cost-Effectiveness of Fleet Options



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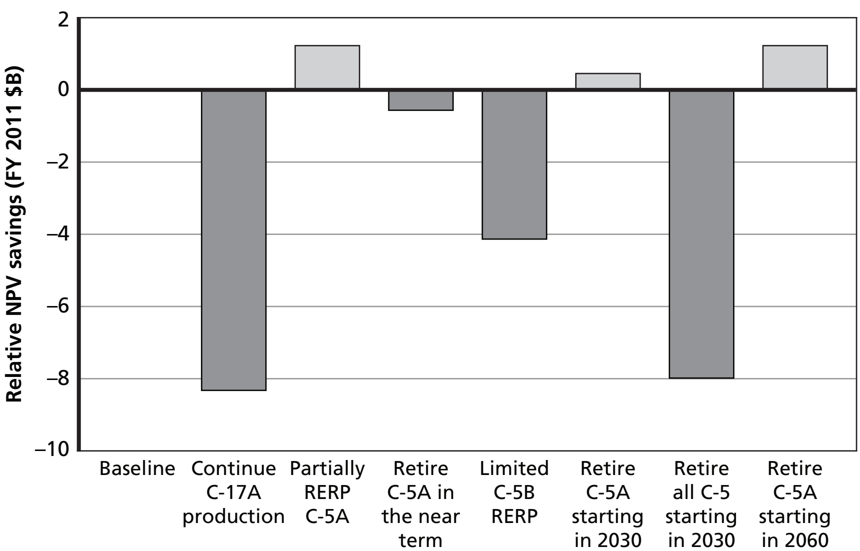
cated by the color, and similarly for the other rows. This figure shows that a new build outsize and oversize aircraft (BWB, SBW-75, C-84X) could be cost-effective as part of a single-aircraft fleet or a mixed-aircraft fleet. We also found that a commercial-derivative aircraft (the C-767) could be cost-effective in a mixed-aircraft fleet along with an outsized and oversized aircraft. We also found that the An-124 could be cost-effective. As discussed earlier in this document, we assumed this aircraft had no nonrecurring costs. However, because this option also has other considerable issues related to its foreign manufacture, we did not consider it further.

Figure 7.2 shows the cost-effectiveness of the different retirement options relative to the baseline for the C-767 + BWB-100++ case. Although this figure is for a single case, the results are relatively consistent across all fleet options. The figure shows that converting C-5Bs to C-5Ms is cost-effective (i.e., a limited C-5B RERP program is not cost-effective), that converting C-5As to C-5Ms *might* be cost-effective, and that the best retirement date for the C-5As is after the C-17As and

Figure 7.2
Cost-Effectiveness of Retirement Options



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the C-5Ms are retired in 2060. In addition, continuing production of the C-17A is not cost-effective.

This research led to several major conclusions. The analysis considered both NPVLCC and annual funding profiles, and the following discussion includes conclusions on both.

Options for the C-5 and C-17A Fleet

RERPing the C-5Bs is cost-effective. The 2010 USAF plan is to RERP all C-5Bs into C-5Ms. This will result in a total of 52 C-5Ms. We found this option to be cost-effective.

RERPing a portion of the C-5A fleet would be cost-effective if the cost and resulting availability were similar to those for RERPing the C-5Bs. The 2010 USAF plan calls for retiring a portion of the C-5A fleet while keeping the remaining C-5As to meet the airlift requirement. Our analysis showed that it is more cost-effective to RERP a portion of the remaining C-5As into C-5Ms and retire additional C-5As. Since the C-5M is more effective per tail than a C-5A, additional C-5As could be retired while still meeting the overall requirement for airlift. This analysis assumed that a C-5A could be RERPed into a C-5M for the same cost as the C-5B RERP and that the resulting C-5M is equally as effective as a C-5M derived from a C-5B.

A C-17A SLEP is cost-effective, with SLEP costs less than \$35 million to 95 million, depending on the follow-on aircraft option that is chosen and available. It is widely accepted that the life-limiting component of the C-17A is the upper wing skin and that all other components have either significant life remaining or very low-cost mitigation procedures. Our analysis did not assess the cost to do a C-17A SLEP of this component. A SLEP analysis requires a substantial engineering assessment of the structural issues, potential mitigation and repair approaches, and cost. This was beyond the scope of this work. This analysis identified the break-even cost point for all the aircraft fleet procurement options we evaluated and found that, for a

SLEP to be cost-effective, the SLEP cost needed to range from $35 million to 95 million. A $35 million per aircraft SLEP is the break-even cost point for the most cost-effective fleet procurement option considered, the advanced BWB. When the engineering analysis of the SLEP option has been conducted and its cost estimated, this analysis can be used to provide insight into the cost-effectiveness of pursuing a SLEP option rather than recapitalizing the fleet with new aircraft.

Options for the Follow-On Fleet

A highly advanced conceptual design BWB aircraft is always the most cost-effective option. Our analysis showed that a highly advanced aircraft is the most cost-effective way to recapitalize the fleet. This option resulted in a cost savings of nearly $40 billion NPVLCC over a new-design (current technology) C-5M-like aircraft. However, design and development of the BWB present significant technological risks, and substantial RDT&E expenditures would be required for years prior to first delivery.

Absent a new revolutionary aircraft design, procurement of a commercial-derivative aircraft for bulk cargo followed by later procurement of an outsize and oversize–capable aircraft is the most cost-effective option. We found that procurement of a commercial-derivative aircraft—such as a militarized Boeing 767-300F followed by an outsize and oversize–capable aircraft with less-advanced technology (such as a box-wing or new-design, current-technology C-5M-like aircraft)—is more cost-effective than a fleet composed exclusively of either of these outsize and oversize–capable aircraft alone. This is because a significant portion of the requirement is bulk cargo that can be transported on a commercial-derivative aircraft, thus reducing the number of oversized and outsized cargo aircraft needed.

The procurement bow wave can be delayed by 10 to 15 years with a mixed fleet consisting of a commercial-derivative aircraft. This analysis showed that procuring a commercial-derivative aircraft before procuring an outsize and oversize–capable aircraft delayed the

peak spending by about 12 years compared with procurement of an outsize and oversize–capable aircraft alone due to the delay in RDT&E spending for the new-design aircraft. This delays the beginning of the ramp-up in annual spending for the mixed fleet by about eight years, and the slope is less steep than for an outsize and oversize–aircraft single-fleet option.

A mixed fleet of a commercial-derivative aircraft followed by a new oversize and outsize–capable military airlifter hedges against technological risk. Since the technological risk for a new-design advanced aircraft may result in much higher costs than our assumptions and/or delays, a hedging strategy using a current-technology commercial-derivative aircraft may be prudent. Such a mixed fleet would hedge against technological risk by permitting time to develop the technology for the new outsize and oversize–capable aircraft. This would push the decision on what advanced aircraft to procure into the future and permit a higher-confidence decision on the technological risk.

Low-rate C-17A production is an inferior option to reduce the spending bow wave and has earlier peak spending, higher near-term cost, and higher total NPVLCC. We considered keeping the C-17A line open and running at a very low rate because this would permit recapitalization of the fleet without the need for RDT&E spending. This option, however, is inferior along every dimension we analyzed. Although the near-term peak is lower than for other options, it occurs years earlier. In addition, the annual spending is higher every year for the next 15 to 30 years, depending on which fleet option is developed (15 years for a single-fleet option consisting of BWBs alone and 30 years for a mixed fleet of C-767s and an outsize and oversize–capable aircraft). Essentially, this option procures C-17As earlier than needed and retires aircraft early, with life remaining. This lowers the fleet O&S cost because of the lower average age, but that reduction does not cover the procurement cost. Finally, and perhaps most important, this option has a higher NPVLCC than other options considered.

APPENDIX A

Exemplar Effectiveness Calculation

Computing Mission and Route Requirements

Figure A.1 illustrates the methodology we used to compute the number of missions needing to be flown on each route on each day. This example shows just three routes, far fewer than the TPFDD data actually contain. The first route, between Dover Air Force Base, Delaware (KDOV), and Ramstein Air Base, Germany (ETAR), has two delivery windows; the first window requires the delivery of 350 pallet train equivalents and requires that this cargo arrive no earlier than day 2 and no later than day 11. Similarly, the second window requires the delivery of 100 pallet train equivalents and requires that this cargo arrive no earlier than day 17 and no later than day 20.

In this example, if the aircraft that needs to meet this demand can carry 36 pallets, at most three missions per day would be necessary. Figure A.2 shows that this demand can indeed be met with a maximum of three missions per day.[1] This figure also shows that the mission assignment algorithm flies missions as early as possible but that the maximum missions per day is minimized. For example, the second delivery requirement between Charleston Air Force Base, South Caro-

[1] The example requires only three missions per day, which would lead to integer rounding issues; however, the full TPFDD requires many more missions, so integer issues are no longer important.

Figure A.1
Example Daily Demand for Three Routes

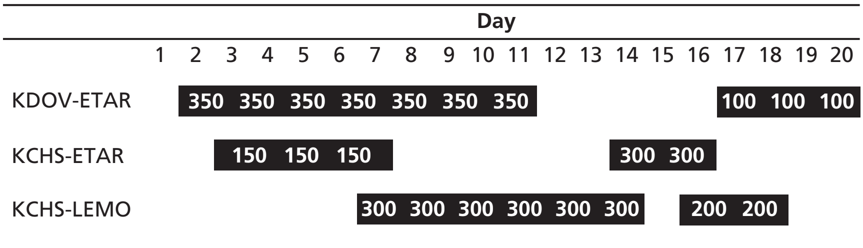

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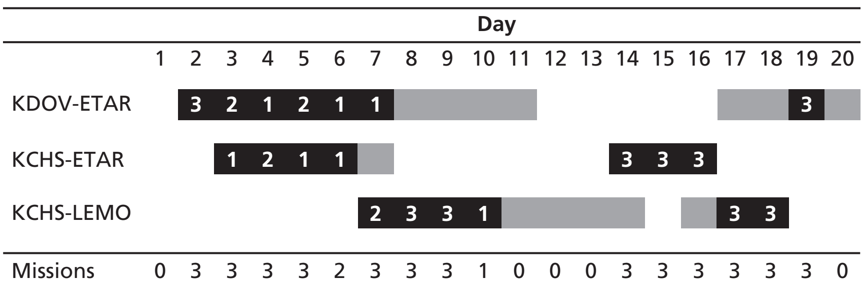
Figure A.2
Example Daily Missions Required to Meet Demand



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lina (KCHS), and ETAR requires a total of nine missions (300 ÷ 36 = 8.33), so there is no way to meet this demand with fewer than three missions per day. Now, given that the fleet is capable of three missions per day, the fleet is utilized to its maximum to fully deliver four of the six delivery window requirements ahead of schedule. In addition to knowing that the maximum number of daily missions in this example is three, it is also possible to compute the number of missions per route. In this example, a total of 13 missions are flown between KDOV and ETAR, 14 missions flown between KCHS and ETAR, and 15 missions flown between KCHS and Moron Air Base, Spain (LEMO) (see Figure A.2). Note that although the total delivery requirement for both KDOV-ETAR and KCHS-LEMO is the same, 450 pallets, the

number of missions flown is not the same because of integer effects when the total demand of 450 pallets is divided differently between the two delivery windows.

Computing Fleet Size and Relative Aircraft Effectiveness

Figure A.2 shows the number of maximum daily missions and the number of missions per route to meet the demand. The aircraft flight model was run for each route to compute a mission time. Knowing the mission time for each route, the mission-weighted average mission time can be calculated. Multiplying this average mission time with the maximum number of daily missions gives the number of MC aircraft required to meet the demand.

To calculate the relative effectiveness of C-X to C-5M, the number of MC C-5Ms needed to deliver the C-X compatible cargo is divided by the number of MC C-Xs needed to deliver that same cargo. For example, if it takes 100 MC C-Xs or 50 MC C-5Ms to deliver the C-X compatible cargo, the relative effectiveness of C-X to C-5M would be 0.5. Conversely, if it takes 25 MC C-Xs or 50 MC C-5Ms to deliver the cargo, the relative effectiveness would be 2. The second cargo group, the cargo that is not C-X compatible, gives us the number of MC C-5Ms required to carry that cargo. If the number of C-5M aircraft is zero, meaning that there is no incompatible cargo, the C-X can carry all the cargo. If, for example, the C-X incompatible cargo requires 20 C-5Ms, this is the portion of the fleet requiring an aircraft capable of carrying that cargo. Continuing the example, if the total demand (all cargo, both C-X compatible and C-X incompatible) requires 100 C-5Ms, the C-X can only constitute 80 percent of the intertheater fleet, in terms of C-5M–equivalent aircraft.

A subtlety of this analysis is that, when the cargo is divided into the two groups, it is generally true that the sum of MC C-5Ms required to deliver the C-X compatible cargo and of MC C-5Ms required to deliver the C-X incompatible cargo is greater than the number of MC C-5Ms required to deliver all the cargo in aggregate. This can easily be understood with a simple example. Imagine that a mission has two

pieces of cargo to deliver—one is C-X compatible and one is not. This means that the number of MC C-5Ms required to carry the C-X compatible cargo is one, and the number of C-5Ms required to carry the C-X incompatible cargo is one, so the sum is two. However, if the two groups are aggregated, assuming that they fit on a single C-5M simultaneously, only one MC C-5M is required. To address this issue, the total demand is expressed in terms of two quantities. These two quantities are the minimum number of MC C-5M aircraft required and the number of MC C-X aircraft required to deliver all the remaining cargo. The minimum number of MC C-5M aircraft required is simply the number of MC C-5Ms required to deliver all the C-X incompatible cargo. The number of MC C-X aircraft required to deliver all the remaining cargo is the difference between the number of MC C-5Ms required to deliver all the cargo and the minimum number of MC C-5Ms required to deliver the C-X incompatible cargo, divided by the relative effectiveness of C-X to C-5M. In the previous example, it took 20 MC C-5Ms to deliver all the C-X incompatible cargo and 100 MC C-5Ms to deliver all the cargo. If it takes 90 MC C-5Ms or 45 MC C-Xs to deliver all the C-X compatible cargo, the relative effectiveness of C-X to C-5M is 2. The TPFDD demand can then be said to require 20 MC C-5M–equivalent aircraft and 40 C-X aircraft—$(100–20) \times 45 \div 90 = 40$.[2]

[2] Using the effectiveness of C-5M relative to other aircraft, the 20 C-5M equivalents can be an appropriate number of any other aircraft capable of carrying the cargo.

APPENDIX B

Aircraft Flight Time Modeling Details

To calculate aircraft flight times and distances, we used the aircraft specifications and the given mission parameters: mission distance, mission payload, temperature, takeoff field elevation and length, and landing field elevation and length. We then used the following procedure to fly the mission:

1. Select a ramp weight that is the lesser of the maximum ramp weight and the MGTOW plus STTO fuel weight.
2. Compute the CFL using the gross takeoff weight (ramp weight selected in Step 1 minus STTO fuel weight), field elevation, and temperature.
3. If the CFL computed in step 2 is longer than the actual field length, decrease ramp weight until the CFL equals the actual field length.
4. Account for fuel burned and time spent during STTO.
5. Compute the optimum initial cruise altitude based on takeoff weight.
6. Look up the fuel burn, distance, and time to climb based on takeoff weight, field elevation, and initial cruise altitude.
7. Compute the fuel burn and time to cruise using the initial cruise weight and cruise distance.
8. Account for fuel and time spent during approach and landing.
9. Compute payload delivered by subtracting aircraft OEW and reserve fuel from landing weight.
10. Compare payload delivered to mission payload. If the payload delivered is greater than the mission payload, decrease ramp

weight and repeat steps 2 through 9 until payload delivered equals mission payload. If the payload delivered is less than the mission payload, add a tech stop to the mission, i.e., decrease the distance of each leg, and return to step 2.

For the cruise segment of flight, we fitted a quadratic to the optimum altitude and Mach number at three weights. Multiplying the optimum Mach number by the speed of sound at the optimum altitude for each weight yielded the optimum aircraft speed at each weight.[1] We used the quadratic function to fit the optimum speed and optimum specific range at each of the three weights. Integrating the specific range function and knowing the initial weight and the distance traveled during cruise produced the weight at the end of cruise. This allowed us to compute the cruise time by integrating the specific range function divided by the velocity function of the aircraft as a function of aircraft weight.

Previous RAND research had requested 960 data points to describe the cruise segment of flight. Examining the data in detail, it became apparent that these data points represented smooth curves, which were easy to represent analytically. To illustrate this, Figure B.1 shows an exemplar specific range data request from the USAF Intratheater Airlift Fleet Mix Analysis (UIAFMA).[2] The orange dots represent the specific range at optimum altitude and Mach number. The UIAFMA relied on linear interpolation between these points, which formed a piecewise continuous function, shown as a solid orange line. We fitted a quadratic to the data, shown as a dashed gray line, and the R^2 was better than 0.999. Similar analysis for optimum altitude and Mach number as a function of weight showed that the agreement was

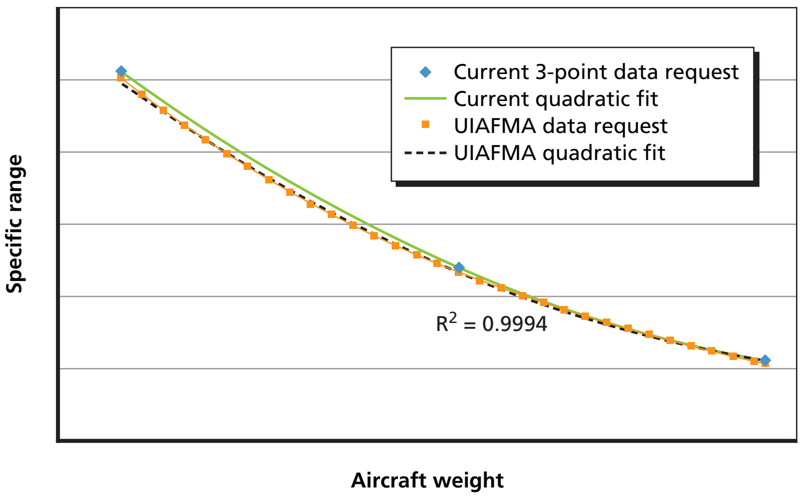
[1] In appropriate units, the speed of sound squared is equal to the ratio of specific heats times the universal gas constant for air times the temperature at altitude. Standard temperature is 15°C at sea level and; this drops by 1.98°C per 1,000 ft in the troposphere, and is constant at –56.5°C in the tropopause.

[2] Documented in Michael Kennedy, David T. Orletsky, Anthony D. Rosello, Sean Bednarz, Katherine Comanor, Paul Dreyer, Chris Fitzmartin, Ken Munson, William Stanley, and Fred Timson, *USAF Intratheater Airlift Fleet Mix Analysis*, Santa Monica, Calif.: RAND Corporation, MG-824-AF, October 2010, Not available to the general public.

also good here. This made the authors confident that a quadratic relationship between specific range and weight was justified, and that the contractor data request could be reduced from 960 points in cruise to nine (three for specific range, three for altitude, and three for Mach number).

As the figure shows, the three-point data curve is higher than the previous UIAFMA data. This could be attributed to updates in the contractor's model, changes between aircraft blocks, or the fact that UIAFMA relied on a discreet data request that may not have captured the optimum. Despite this difference, the use of a quadratic appears robust and greatly reduces the amount of data required to describe aircraft flight performance.

Figure B.1
Exemplar Quadratic Fit to Specific Range Data



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